ILRI publication 46

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A simulation model on Crop Irrigation Water Requirements

M.G. Bos
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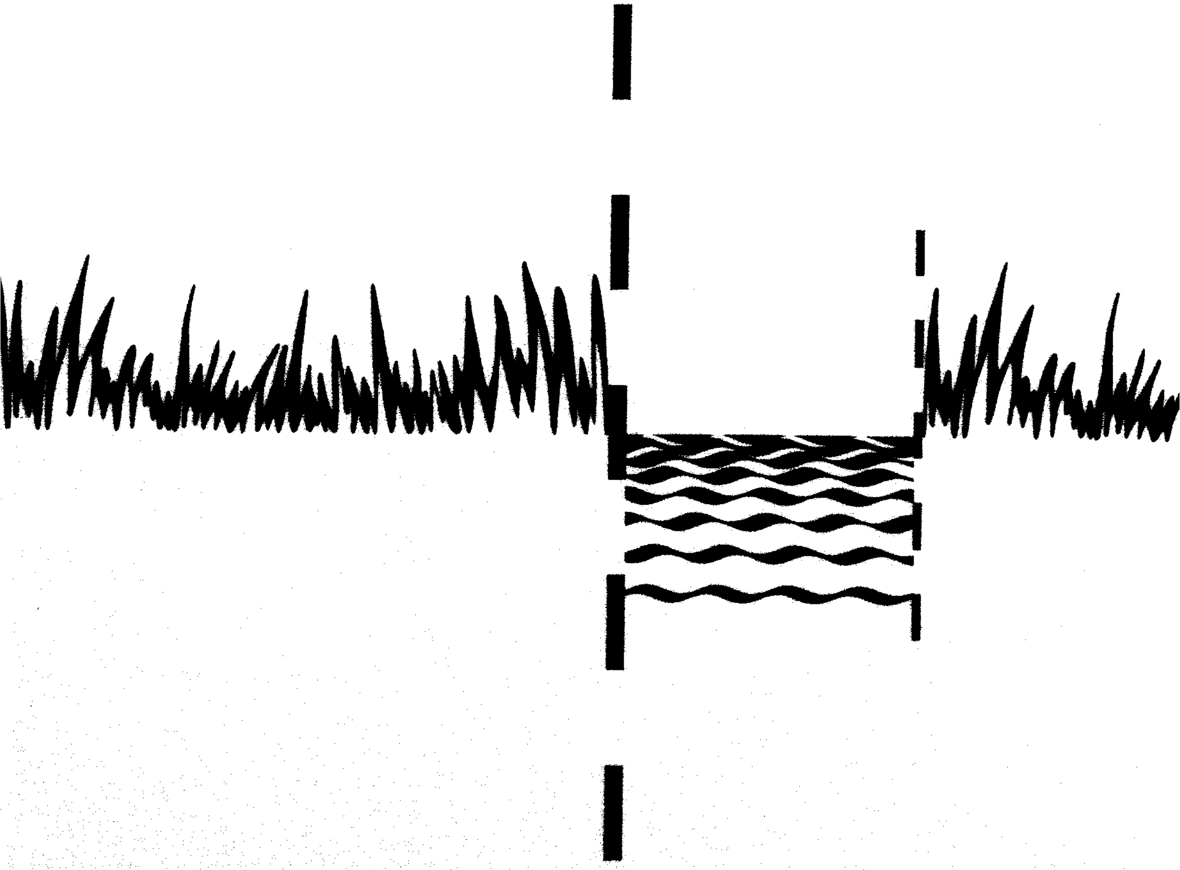

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ALTERRA-ILRI

International Institute for Land Reclamation and Improvement/ILRI,
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ILRI is a business unit of Alterra, Green World Research, a land and water organisation that operates under the larger auspices of the Wageningen University and Research Centre.

The aims of ILRI are:
- To collect information on land reclamation and improvement from all over the world;
- To disseminate this knowledge through publications, courses, and consultancies;
- To contribute – by supplementary research – towards a better understanding of the land and water problems in developing countries.

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Abstract

CRIWAR 2.0 calculates the crop irrigation water requirements of a cropping pattern in an irrigated area. The crop irrigation water requirement consist of two components: potential evapotranspiration, ET_p, minus the effective precipitation, P_e.

The input data of CRIWAR 2.0 are organized through three files; a general data file on the irrigated area, a meteo data file and a cropping pattern file. The cropping pattern file can be composed of 50 CRIWAR programmed crops and of any user defined crop. For a user-selected combination of general data, meteo data and cropping pattern, CRIWAR creates tables and graphs giving; reference evapotranspiration, crop irrigation water requirements per 10-day period or month, cropping intensity, cropping pattern, effective precipitation, etc. All tables and graphs can be imported into commonly used word-processing software.

Following the 'user manual' part of this book (Chapters 2 through 4), this manual gives theory and information on evapotranspiration (Chapter 5), effective precipitation (Chapter 6), capillary rise (Chapter 7) and how to transfer the crop irrigation water requirements into the irrigation water requirements of an irrigation command area (Chapter 8).

Preface

To effectively accomplish irrigation management it is important that the water requirements are known at different management levels within the irrigated area. CRIWAR calculates the irrigation water requirements of a complex cropping pattern. This manual, however, gives additional information on capillary rise as a source of water and on the method by which the CRIWAR output can be used to estimate the water requirements at the delivery structure of an irrigation command area.

CRIWAR can be a useful tool in the design of irrigation systems, because it calculates the summarized irrigation water requirements of a complex cropping pattern for a large area, fast and with ready to use output tables and graphs. This allows the design engineer to review alternative cropping patterns under various meteorological conditions.

Furthermore, CRIWAR can be a helpful tool in the management of operational irrigation projects with frequent changing cropping patterns and in the studies on performance assessment of irrigation projects.

This publication is the result of a joint activity between the Wageningen University of Agriculture (WAU), the Winand Staring Centre for Integrated Research on Rural Areas (SC-DLO) and ILRI. During the preparation of this second version assistance was received from P.Kabat (SC-DLO) and K.J.Lenselink (ILRI).

CRIWAR Version 2.0 was developed for computers which operate under the MS-DOS environment. The software was written by H.R.Ramnandanlal and R.A.L.Kselik.

M.G.Bos
J.Vos
R.A.Feddes

Wageningen
January 1996

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Symbols

a = fraction of extra-terrestrial radiation on overcast days (–)
$a+b$ = fraction of extra-terrestrial radiation on clear days (–)
c = dimensionless adjustment factor
C = height of capillary rise (m)
c_p = specific heat of dry air at constant pressure (J/kgK)
d = displacement height because of crop height (m)
d_r = relative distance between the earth and the sun (–)
E_a = isothermal evaporation rate (kg/m^2 s)
E_o = open water evaporation rate (kg/m^2 s)
$e_{s,sat}$ = saturated vapour pressure at the evaporating (water) surface (kPa)
ET_g = reference crop evapotranspiration rate according to the FAO modified Penman method (mm/day or mm/month)
ET_h = reference crop evapotranspiration rate according to the Penman-Monteith method (mm/day or mm/month)
ET_p = potential crop evapotranspiration rate (mm/day or mm/month)
e_z = prevailing vapour pressure in the external air, at the same height as T_z is measured (kPa)
$e_{z,sat}$ = saturated vapour pressure at temperature T_z (kPa)
f = a correction factor which depends on the depth of the irrigation water application per turn [–]
F = force (N)
$f(u)$ = wind function; $f(u) = 1 + 0.864u_2$
g = acceleration due to gravity ($g = 9.81$ m/s^2)
G = heat flux density into the water body or soil (W/m^2)
h = soil water pressure head, $p\rho/g$ (m)
H = flux density of sensible heat into the air (W/m^2)
H = the altitude above mean sea level (m)
h_{hydr} = hydraulic head (m)
h_{pr} = the soil water pressure head, $p/\rho g$ (m)
K = von Kármán constant (–); equals 0.41
k = hydraulic conductivity (m/d)
k_c = crop coefficient
n = daily duration of bright sunshine (h)
N = day length (h)
p = pressure energy per unit of volume (Pa)
P = precipitation (mm/month)
p_a = atmospheric pressure (kPa)
P_e = effective precipitation (mm/month)
q = vertical flow rate per unit area (m/d)
r = equivalent radius of the tube (m)
r_a = aerodynamic diffusion resistance, assumed to be the same for heat and water vapour (s/m)

R_A = extra-terrestrial radiation flux density, or Angot value (W/m^2)
r_c = 'big leaf' stomatal diffusion resistance (s/m)
R_n = energy flux density of net incoming radiation (W/m^2)
R_{nl} = net long-wave radiation flux density(W/m^2)
R_{ns} = net short-wave radiation flux density(W/m^2)
R_s = solar radiation flux density(W/m^2)
s = standard deviation
T_{av} = average air temperature (°C); $T_{av} = (T_{max} + T_{min})/2$
TK_{max} = maximum absolute temperature (K)
TK_{min} = minimum absolute temperature (K)
T_p = statistical value that is exceeded by a random variable, normally distributed, with zero mean, and with standard deviation units
T_s = temperature at the evaporating (water) surface (°C)
T_z = air temperature at a height z above the surface (°C)
u_2 = wind speed measured at 2.0 m above ground surface (m/s)
u_z = wind speed measured at height z (m/s)
V_l = inflow from other sources to the conveyance system (m^3/period)
V_c = volume of irrigation water diverted or pumped from the river or reservoir (surface water source) (m^3/period)
V_f = volume of irrigation water delivered to the fields during the period under consideration (m^3/period)
V_m = volume of irrigation water needed, and made available, to avoid undesirable stress in the crops throughout the growing cycle (m^3/period)
z = elevation head, being positive in upward direction (m)
z = height at which wind speed is measured (m)
z_{om} = roughness length for momentum (m)
z_{ov} = roughness length for water vapour (m)

α = albedo, or canopy reflection coefficient (–);
α = contact angle of water with the tube (rad);
γ = psychrometric constant (kPa/°C)
δ = declination of the sun (rad)
Δ = proportionality constant $de_{air,sat}/dT_{air}$ (kPa/°C)
ε = ratio of molecular masses of water vapour over dry air (–)
λ = latent heat of vaporization (J/kg)
λE = flux density of latent heat into the air (W/m^2)
ρ = density of water ($\rho = 1000\ kg/m^3$)
ρ_a = density of moist air (kg/m^3)
σ = surface tension of water against air ($\sigma = 0.073\ kg.s^{-2}$ at 20°C)
σ = Stefan-Boltzmann constant (equals $5.6745 \times 10^{-8}\ W/m^2\ K^4$)
φ = latitude (rad); northern latitude positive; southern negative
ω_s = sunset hour angle (rad)

1 Introduction

1.1 What Does CRIWAR Calculate?

CRIWAR calculates the irrigation water requirements (either per month or per 10-day period) of a cropping pattern in an irrigated area, for various stages of crop development throughout the crops' growing season. The crop irrigation water requirements consist of the potential evapotranspiration, ET_p, minus the effective precipitation, P_e.

The potential evapotranspiration, ET_p, is the volume of irrigation water required to meet the crops' potential evapotranspiration during a specific time period, under a given cropping pattern and in a specific climate. As will be explained in Chapter 5, CRIWAR calculates the ET_p on the basis of two (user-selected) alternative methods of computing the reference evapotranspiration: the FAO Modified Penman Method, ET_g, and the Penman-Monteith Method, ET_h (Penman 1948; Doorenbos and Pruitt 1977; Monteith 1965; Verhoef and Feddes 1991). To determine ET_p, these reference values of ET are then multiplied by a crop coefficient, k_c. Hence

$$ET_{p,fao} = k_c\, ET_g \tag{1.1}$$

or

$$ET_{p,pm} = k_c\, ET_h \tag{1.2}$$

Subsequently, the calculated ET_p-value is reduced by the effective part of the precipitation, P_e (Chapter 6). We use the definition of effective precipitation that corresponds with the ICID terminology on the 'field application ratio' and the related efficiencies at crop production level (Bos 1980; Bos and Nugteren 1974; ICID 1978):

> *'Effective precipitation is that part of total precipitation on the cropped area, during a specific time period, which is available to meet evapotranspiration in the cropped area.'*

As will be discussed in Chapter 6, P_e is estimated with the method developed by the U.S. Soil Conservation Service (USDA 1970).

1.2 ET_p - P_e in the Field Water Balance

We assume that the irrigation water is applied to the crop by a surface irrigation method, by sprinkler, or by micro-irrigation. Figure 1.1 shows the water balance of an irrigated field. As can be seen, the ET_p and the precipitation, P (and the related P_e) quantify only two of the eight components of the water balance. The available soil water in the rootzone, and the capillary rise of water from the saturated zone

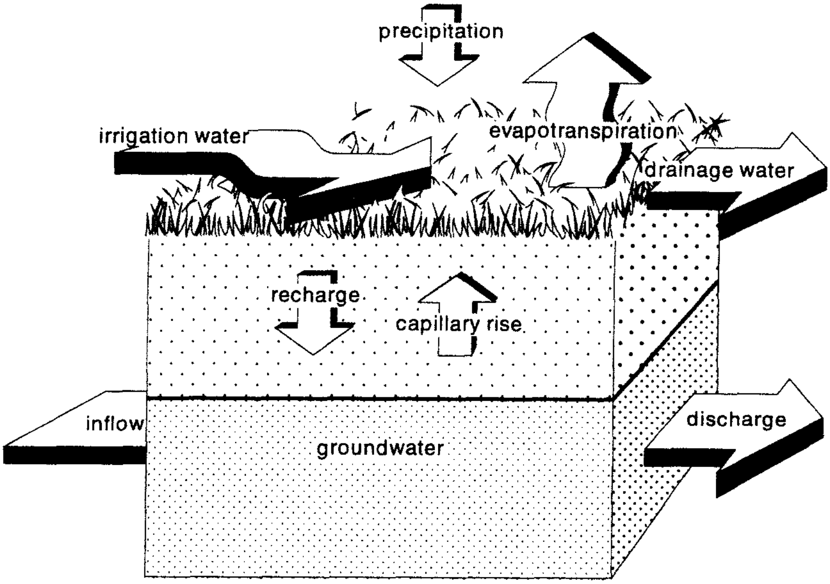

Figure 1.1 Schematic water balance in an irrigated field (Bos 1984)

into the rootzone, are not incorporated in CRIWAR. The available water in the rootzone cannot be simulated because it depends heavily on site-specific soil physical information and on the rooting depth of the crop (which is a function of crop variety, soil type, groundwater depth, and climate). Such information is not normally known for any crop during its growing season.

If the depth to the watertable is shallow (less than 3 m) and the soil is fine-textured, capillary rise can contribute a significant volume of water to the rootzone. For the watertable to remain stable, however, there must be a lateral flow of groundwater into the irrigated area; otherwise, capillary rise will decrease with the falling watertable. Because groundwater flow is not simulated in CRIWAR, the capillary component is not corrected for in the crop irrigation water requirements. Chapter 7 explains how to correct the CRIWAR-calculated crop water requirements for the readily available stored soil water and for the contribution from groundwater.

To transfer crop irrigation water requirements into irrigation water requirements at the field inlet, at the supply structure of the tertiary unit, and at the head inlet structure of the irrigation system, the CRIWAR-calculated crop irrigation water requirements must be multiplied by water supply ratios. These ratios will be discussed in Chapter 8.

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2 Getting Started

2.1 Introduction

You should have received one 3.5-inch distribution disc with CRIWAR. The disc contains the executable program and the overlay and configuration files that you need to run CRIWAR. The disc also contains some samples of crop factor files and meteo files. The CRIWAR software is regularly maintained. The date until which the software has been maintained is shown on the title page (third introductory screen). The latest developments are given in the README.CRW file.

CRIWAR operates in the MS-DOS environment. Version 2.0 requires about 480 Kb of memory. A hard disc drive is recommended, as is a 80286 microprocessor or higher.

The distribution disc is protected against illegal copying by a software protection system. This system installs one 'token' on the disc drive on which the CRIWAR directory is located. Each time that CRIWAR is started, it will check for the presence of that token. If it is not found, CRIWAR will abort and show a warning on the screen. The original distribution disc contains two tokens of CRIWAR. You can therefore install CRIWAR on two different computers. For safety's sake, however, we recommend that you keep one token on the original distribution disc.

If you want to move CRIWAR to another computer, or to another hard disc on your computer, we recommend the following procedure:

1 From within CRIWAR, use the **Make Backup** option (Section 2.4.2) to backup all data files to a CRIWAR directories backup disc (disc not included with CRIWAR).
2 Return to MS-DOS.
3 Insert the original distribution disc in the disc drive. (Any other disc will not work.)
4 Type **ccmove c: a:** to move the 'token' (e.g. if the CRIWAR directory is on Drive **C:** and the distribution disc is in Drive **A:**).
5 Then re-install CRIWAR on the new computer, or to the new drive, using the standard installation procedure of Section 2.2.
6 Finally, run CRIWAR and use the **Read Backup** option (Section 2.4.3) to read files from the CRIWAR backup disc.

The same procedure should be used to install an updated version of CRIWAR.

2.2 Installation

Automatic Installation

To install CRIWAR on a hard-disc system (e.g. on the Drive C):

1 Insert the distribution disc in the A-Drive, type **a:** (or **b:** if you are using the B-

Drive), and hit **enter**.
2 Type **instcrw** and hit **enter** again.

The program now creates a sub-directory CRIWAR on Drive C (C:\CRIWAR), and subsequently copies the files. Messages appear on the screen to show the installation progress. If your computer already has a sub-directory C:\CRIWAR, existing files may be lost. You will be asked 'Do you want to proceed with the installation ? Yes/No'

Manual Installation
If, for some reason, the installation program does not run as expected, you can install CRIWAR manually as follows:

1 Create a directory for CRIWAR on the user-selected hard drive.
2 Select this new directory as default directory.
3 Copy all files (except INSTCRW.EXE) from the installation disc to the newly-made directory.
4 Install the software protection by typing: **ccmove a: c:**
where **a:** and **c:** indicate the drive containing the installation disc and the drive on which CRIWAR is installed. You should replace these drive letters by the appropriate ones if necessary.

To run CRIWAR from a hard-disc system (C-Drive):
1 Move to the C: directory [C:\>]
2 Go to the directory C:\CRIWAR\. To get there, type **cd\criwar** and hit **enter**.
3 Execute the program; type **crw** and hit **enter**.

Upon typing **crw**, you will see three introductory screens preceding the main menu of CRIWAR. Pressing any key will advance these screens more quickly. The main menu consists of five branches as shown in Figure 2.1.

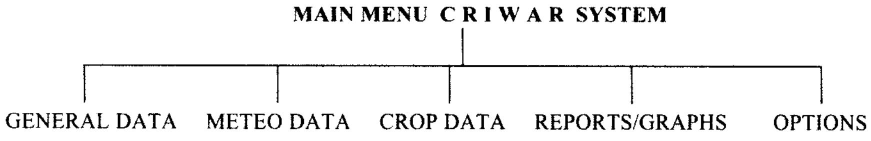


Figure 2.1 The main menu of CRIWAR

The **OPTIONS** branch will be discussed in Sections 2.3 and 2.4. Section 2.5 will explain the menu structure and the general procedure on how to move through the menu. (The other branches will be treated in Chapters 3 and 4.)

2.3 Initial Settings

When you enter the program for the first time, you need to tell CRIWAR in what system of units you want to work. The procedure for this is as follows:

1 Move the cursor to the **OPTIONS** menu branch with the **arrow** keys.
2 Hit **return**.
The screen then displays Figure 2.2.

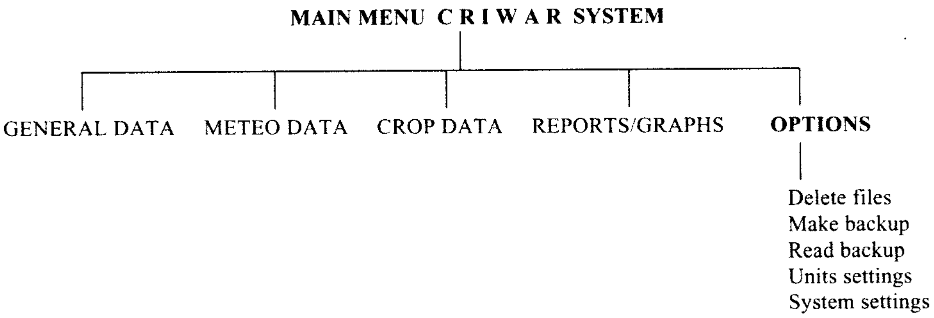


Figure 2.2 The Options sub-menu of CRIWAR

The first three sub-menus of the **OPTIONS** branch relate to file handling. They will be explained in Section 2.4. Before using CRIWAR, you should consider the fourth and fifth sub-menus. Hence:
3 Move the cursor to the **Units settings** menu choice with the **arrow** keys.
4 Hit **return**.

2.3.1 Units Settings

Under **Units settings**, you can enter units for length, area, velocity, precipitation, and temperature. These can be changed at any time, and the program will simply convert all dimensions to the new units. The screen will display:

Units Settings

Unit for lengths and heights	**m**	metre
Unit for area	**ha**	hectare
Unit for velocity	**m/s**	metre per second
Unit for temperature	**°C**	Celsius
Unit for precipitation	**mm**	millimetre

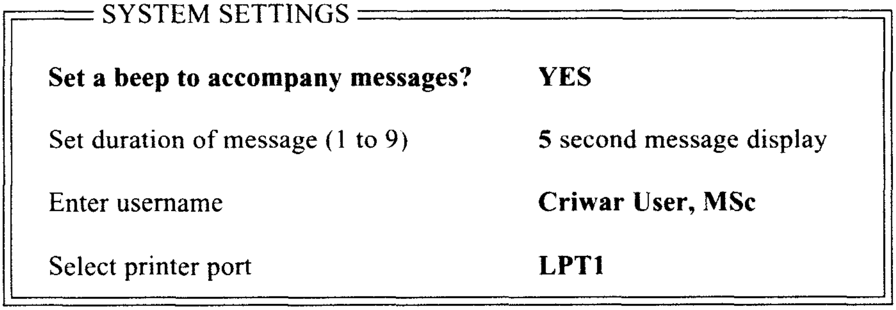
This shows the units in the (default) metric system. The procedure to change them is:
1 Use the **arrow** keys to make a selection if you want to change the units of length, area, velocity, temperature, or precipitation.

2 Hit **return**. The above double-lined window will disappear, and will be replaced by a new window containing the units that are available in CRIWAR.
3 Use the **arrow** keys to select the units you want.
4 Hit **enter**. The newly selected units will be shown at the right of the menu window.

To leave this sub-menu and return to the next higher menu level, hit the **Esc** key. A message will be given that the new units have been saved.

2.3.2 System Settings

You can enter the **System settings** menu branch by using the arrow and enter keys. The following menu window, plus selected options, will appear on the screen:



SYSTEM SETTINGS

Set a beep to accompany messages? **YES**

Set duration of message (1 to 9) 5 second message display

Enter username **Criwar User, MSc**

Select printer port **LPT1**

These options can be changed in the following way:
1 Use the **arrow** keys to move the menu bar (highlighted) to the option you want to change.
2 Hit **enter**. The above window will disappear and a new double-lined window will be shown.
3 Select/type new value or name.
4 Hit **enter**.
5 Upon hitting the **Esc** key, you will receive the message 'New settings are saved'.

We recommend setting a beep to indicate that CRIWAR is providing you with information. Messages from CRIWAR will be displayed for the duration you have selected. Hitting any key will make the message disappear more quickly.

We also recommend that you enter your name when using CRIWAR since the user name appears on output reports.

2.4 Directory Handling

CRIWAR maintains sub-directories of general data files, meteo files, cropping pattern files, crop factor files, and output files (Figure 2.3). These directories can be accessed through other MS-DOS programs. The general data file contains information on the site where the irrigated area is located, geographical data on this site, and data on irrigation practices. Output files are stored for each combination of meteo file, cropping pattern, and irrigated area. As was mentioned in Section 2.3, directory handling is located under the **OPTIONS** branch of the main menu. Here, three sub-menus are available: **Delete file**, **Make backup**, and **Read backup**.

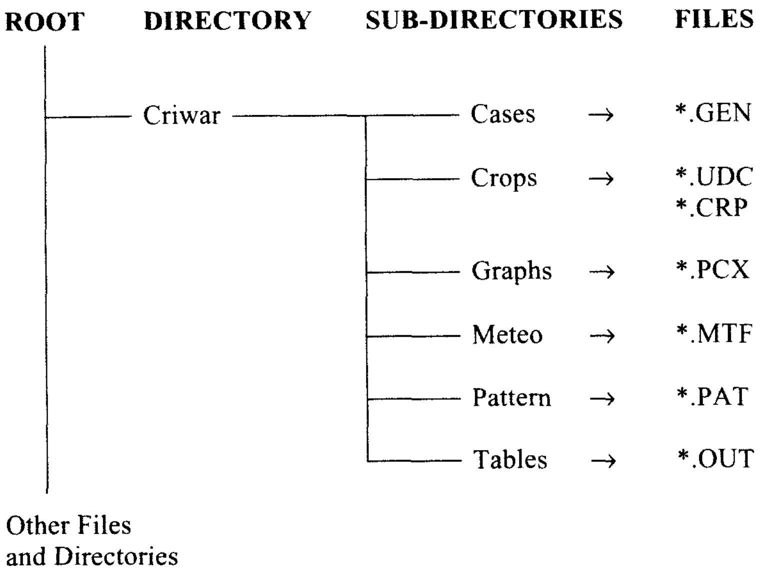


Figure 2.3 Directory structure

2.4.1 Delete Files

Upon entering the **Delete files** option, you will see the following window:

Delete general data files
Delete meteo data files
Delete cropping pattern data files
Delete crop factor files

1 Use the **arrow** keys to select a group of data files.
2 Upon hitting **enter**, you will see the following selection window:

Delete files from: **hard disc**
A drive
B drive

3 Use the **arrow** keys to select the hard disc or a disc in your disc drive.
4 Upon hitting **enter**, you will be shown a list of all files in the directory you have selected.

```
╔═══ SELECT FILES THAT YOU WANT TO DELETE ══════╗
║ File name            Date of creation         ║
║ etc.                                          ║
╚═══ INSERT=select and un-select ═══ ENTER=confirm ═══╝
```

To delete all the data on a file, proceed as follows:
5 Using the **arrow** keys, select a file you want to delete. Please note that CRIWAR does not allow you to delete files related to the area in which you are currently working (i.e. those shown on the screen).
6 Hit **insert**.
7 Move to the next file to be deleted, and repeat Steps 5 and 6.
8 Hit **enter** and read warning/question on screen and answer **Yes** or **No**.

2.4.2 Make Backup

CRIWAR keeps track of directories containing saved meteo, cropping pattern, crop factor, and output files. If you choose **Make backup** under the **OPTIONS** menu, CRIWAR will ask you if the backup is to be made on the A or B-Drive. The backup procedure is:
1 Insert formatted disc in either Drive A or B.
2 Toggle to the appropriate A or B-Drive and hit **enter**.
3 CRIWAR will display the list of files in the active directory.
4 Select a file by using the **arrow** keys.

```
╔═══ SELECT FILES (YOU WANT) TO BACKUP ═════════╗
║ File name            Date of creation         ║
║ etc.                                          ║
╚═══ INSERT=select and un-select ═══ ENTER=confirm ═══╝
```

5 Hit **insert**.
6 Move to the next file and repeat Steps 4 and 5
7 Hitting the **enter** key confirms the copying of the selected files.

CRIWAR backs up the meteo files, the crop files, and the output tables. A message will be given that a backup has been made.

2.4.3 Read Backup

Data on the climate (meteo file), the irrigated cropping pattern (crop file), and the general data on a backup disc can be read into the active CRIWAR directory through the **Read backup** sub-menu. The steps to be followed are:

1 Answer A or B to question 'Which drive do you want to use for backup?'.
  Note: If you hit **enter** before the backup disc is in the drive, a warning will be given.

CRIWAR will display:

```
╔════ SELECT FILES (YOU WANT) TO READ ════════════╗
║  File name              Date of creation        ║
║  etc.                                           ║
╚═══ INSERT=select and un-select ═══ ENTER=confirm ═╝
```

2 Using the **arrow** keys, select those files that are to be read into the sub-directory.
3 Hit **insert**.

If you try to read a 'file name' into the directory while the directory already contains a file with that name, you will be asked; 'Do you want to overwrite the data in the CRIWAR directory?' If you toggle to **YES** and hit **enter**, you will lose the old file. (Note: You may want to copy the existing file to a new name before overwriting it.)

4 Hitting the **enter** key will return you to the **OPTIONS** menu system. A message will be given that the backup has been read.
  Hitting the **Esc** key brings you back to the main menu.

A backup CRIWAR file is identical to the CRIWAR file in use. Hence, the **Make backup** and **Read backup** options can be used to transfer CRIWAR files from one machine to another.

2.5 CRIWAR Menu System Basics

The CRIWAR menu system is written in TURBO PASCAL. The menus are set up in a hierarchical format, as shown by the menu system outline in Figure 2.4. We recommend that you go through the menu options a few times with a 'example irrigated area plus related meteo and crop files' just to get the feel of the program.

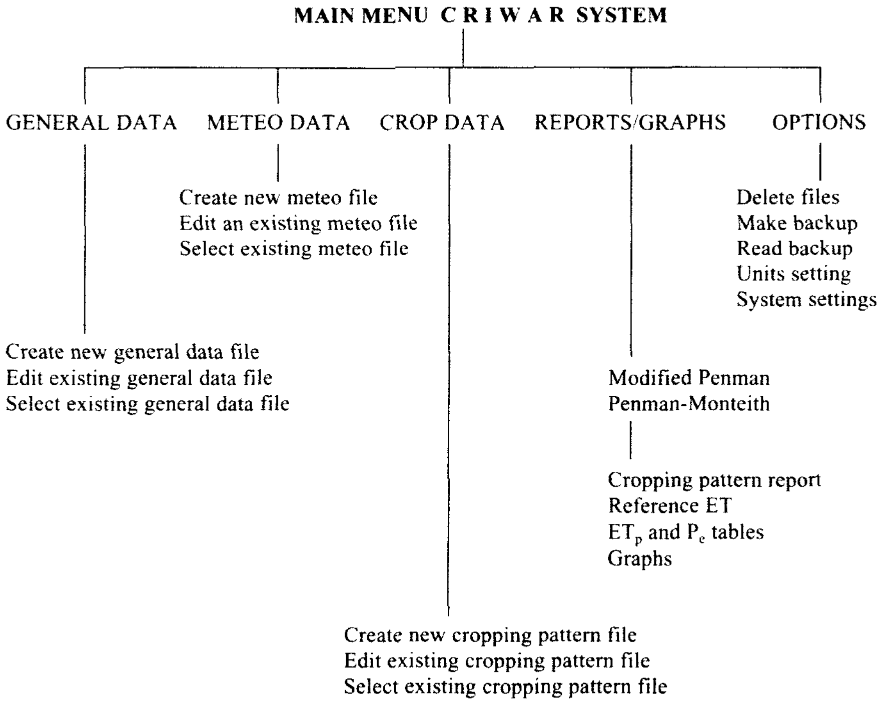


Figure 2.4 The CRIWAR program menu system outline

At any level within the menu system, you can choose the different menu options either by pressing the arrow keys until the desired option is highlighted and then pressing **enter**.

There are two types of menu layout. The options can be given horizontally across the screen (as for the main menu) or vertically below a horizontal menu option. For the horizontal menus, the **left** and **up arrow** keys move you to the left; the **right** and **down arrow** keys move you to the right. For the vertical menus, the **left** and **up arrow** keys move you up; the **right** and **down arrow** keys move you down. The **Esc** key moves you from the menu you are in to the next menu level up. From the main menu, **Esc** starts the procedure for exiting CRIWAR and returns you back to DOS.

There are three or four menu levels, depending upon which menu options you choose. Below these menu options, you will be asked for information, which can be text, numbers, or the selection from a table of choices. Tables of choices are slightly different from menus in that the choices are surrounded by a double-lined box. Choices result in data entry into the database of information or settings, while menu item selections do not.

2.6 Data Entry

To enter text and numerical data on the choices in a double-lined window, the general procedure is:

1. Use the **arrow** keys to highlight the line on which data are to be entered.
2. Press the **enter** key to move to the field. The first double-lined window will disappear, and will be replaced by a new window showing either which data should be entered or the available options from which you can select.
3. Enter the data or select from a shown choice.
4. Press the **enter** key again to record the information.

Most numerical data have an allowable range of values. If you input a value that is out of range, CRIWAR will return to the data entry location after you hit **enter**, and will continue to do so until you either enter a value that is within range, or hit **Esc**. The latter returns the field to the previously saved value.

For some mid-level menus, the menus are simply shown below the higher level menu. For others, no higher level menus are shown. This is dictated by the space limits on the screen and our desire to make the system as easy to use as possible. For some lower level menus, the data relevant to the menu choices are given on the screen below the menus. This is to aid you in deciding which menu choices, if any, you need to select (i.e. according to what data have to be modified).

In the middle of the screen, you will be given information on the data files with which you are currently working. If the space to the right of this block is empty, no file has been selected.

General data file name:
Meteo data file name:
Cropping pattern data file name:
Country:
Name of region or project:
Calculation period per:

Highlighted at the bottom of the screen is a more detailed description of the current menu item. This allows CRIWAR to keep the menu selections to one or two words while still providing you with some detail about what the menu choices represent.

3 Data Entry

3.1 The Main Menu

The main menu of the CRIWAR program consists of the five branches shown in Figure 3.1:

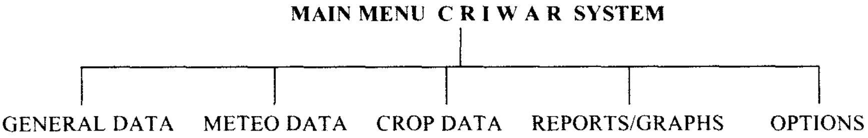


Figure 3.1 The main branches of the CRIWAR 2.0 menu

Except for the initial setup of the CRIWAR options, the main menu is arranged so that you move from left to right. You first select an irrigation project that you want to study (i.e. you select or create a new general data file), and then subsequently select a meteo file and a cropping pattern file (or enter actual data). This chapter deals with those three data entry branches.

3.2 General Data

When you start CRIWAR by entering **crw**, the **GENERAL DATA** branch of the menu will be highlighted. Hitting **enter** gives you the following options:

Create New General Data File
Edit Existing General Data File
Select Existing General Data File

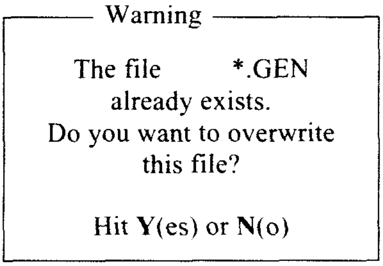
You can select an option by using the **arrow** keys. Upon hitting **enter**, you will see a menu window on the screen.

3.2.1 Create New General Data File

CRIWAR can only calculate the crop irrigation water requirements for a cropping pattern if the geographical location and general project data are known. If no general data file for the region exists, you should then:

1. Select the **Create New General Data File** sub-menu option and hit **enter.**
2. Type the name of the new file (up to 8 characters) and hit **enter**.

If the name of this file already exits in the CRIWAR directory, a warning will appear:

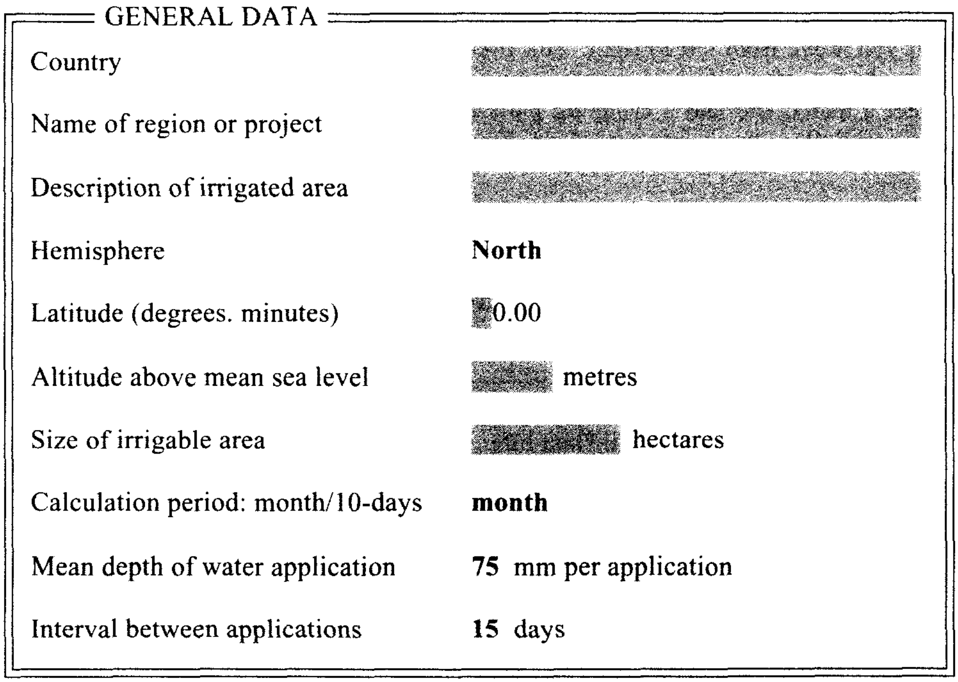

Warning

The file *.GEN
already exists.
Do you want to overwrite
this file?

Hit **Y**(es) or **N**(o)

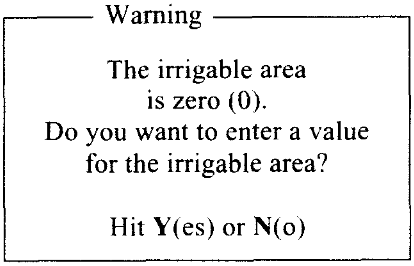
If you enter Yes, all the data in the old file will be overwritten (i.e. lost) as soon as you have saved the new file (by hitting **Esc**). By answering No, you have the opportunity to choose another file name.

CRIWAR will now display the following empty menu window, together with the currently selected (or default) information:


GENERAL DATA

Country	
Name of region or project	
Description of irrigated area	
Hemisphere	**North**
Latitude (degrees. minutes)	0.00
Altitude above mean sea level	metres
Size of irrigable area	hectares
Calculation period: month/10-days	**month**
Mean depth of water application	**75** mm per application
Interval between applications	**15** days

After entering data in all fields, which will be explained in Section 3.2.2, you save the file by hitting **Esc**. The file is then available to CRIWAR for simulations of the crop water requirements. Information on the file will be shown on the screen. CRIWAR does NOT accept incomplete general data files. If you hit **Esc** before you have entered the irrigable area, for instance, CRIWAR will ask:



Warning

The irrigable area
is zero (0).
Do you want to enter a value
for the irrigable area?

Hit **Y**(es) or **N**(o)

Hitting **Y**(es) takes you back to the general data window for completion. Hitting **N**(o) deletes the non-completed general data file and takes you back to the sub-menu.

3.2.2 Entering General Data

Country, Name of Project, and Description of Area

These three options permit you to enter, or change, the location and the description of the irrigated area in the CRIWAR General Data File. These descriptions will be printed in the heading of the related tables. Hence, if you retrieve an existing file from the directory and subsequently edit it to meet new conditions, you should enter a new description. The procedure to change the description is:

1 Hit **enter**. The general data window will be supplemented by a box in which the new description can be entered.
2 Type the new description in the available space and hit **enter**.

You will now be back in the general data window. If other data have to be changed, use the **arrow** keys to move to the option. Hitting **Esc** returns you to the **GENERAL DATA** sub-menu.

Hemisphere, Latitude, and Altitude

To calculate the maximum possible number of hours of bright sunshine and the extra-terrestrial radiation, CRIWAR needs information on the hemisphere and the latitude of the irrigated area, and on its altitude above mean sea level.

The hemisphere is defaulted **North**. To change to South:

1 Select **hemisphere** by using the **arrow** keys, and hit **enter**. The following window will appear:

TOGGLE
North
South

2 Select **South** by using the **arrow** key and hit **enter**. You have now returned to the

menu window with **South** shown at the right in this window.

The procedure to change the latitude and altitude is:

1 Select either **Latitude** or **Altitude** and hit **enter**. The menu window will be supplemented by a 'box' around the data.

2 Type the new data in the available space (degrees and minutes separated by a full stop or the altitude in the selected height units without decimals) and hit **enter**. See Table 3.2 for allowable ranges for latitude and altitude.

Irrigable Area

The irrigable area should be entered in hectares (default) or in acres. The given area represents the 100% value for the cropping pattern. In other words, CRIWAR does not accept a larger cropped area under the menu branch **CROP DATA** than the user-given value. If the sum of sub-areas of the cropping pattern exceeds the given irrigable area, CRIWAR will give a warning on the screen.

Calculation Period

The choice of the calculation period usually depends on the degree of detail of the available meteorological data and data on the cropping pattern. The calculation period is defaulted **Month**. To change to **10-days**:

1 Select **Calculation Period** by using the **arrow** keys, and hit **enter**. The following window will appear:

TOGGLE

Month

10-days

2 Select **10-days** by using the **arrow** key, and hit **enter**. You have now returned to the menu window with **10-days** shown at the right in this window.

The number of days in a calculation period varies with the month under consideration (28, 30, or 31 days). With the 10-day period, each calender month is divided into three periods: the first two periods always have 10 days: the third period has either 8, 10, or 11 days, depending on the month under consideration.

If a meteo file has already been selected and the calculation period of that file differs from the newly selected calculation period, the following warning will appear:

Warning

Calculation Period is
not compatible with the
loaded Meteo File.
Change this period or
load another Meteo File.

Hit **enter**

If no action is taken after this warning, CRIWAR will not generate any reports and graphs!

If, at a later stage, you load a meteo file whose calculation period differs from the loaded general data file (or default month), the following warning will appear:

Warning

Meteo Data do not match
the calculation period.
Do you want to change this
period into ▒▒▒ ?

Hit **Y**(es) or **N**(o)

If you select **N**(o), CRIWAR transfers the meteo data to the calculation period you selected under **General Data**. If you select **Y**(es), CRIWAR loads the selected meteo file and changes the calculation period to that of the selected meteo file. Hence, this changes the earlier selected calculation period! CRIWAR can only generate reports and graphs if the newly selected calculation period is the same as that of the loaded cropping pattern.

Depth and Interval of Water Applications

The mean depth of irrigation water application per turn is used to estimate the effective part of the precipitation (see Chapter 6). For most irrigated areas, this application depth per turn would not exceed the readily available soil water in the rootzone. CRIWAR uses a default value of 75 mm.

CRIWAR uses the frequency of an irrigation water application, or significant precipitation, to determine the crop coefficient, $k_{c,I}$, in the initial stage of crop growth (see Section 5.8.1).

3.2.3 Edit Existing General Data File

You may want to simulate the crop irrigation water requirements for another calculation period or for other irrigation data. If so, you would simply want to edit the existing General Data File. To do this:

1 Select the **Edit Existing General Data File** sub-menu option.
2 Hit **enter**.
3 Type a different name for the new file.
4 Hit **enter**.

All the names of general data files will be shown on the screen as follows:

```
Select General Data File
File Name          Date of Creation
etc.
```

5 Use the **arrow** keys to move through the list of files, and
6 Hit **enter** to copy all data of the selected file to the 'new file'.

The selected file will be shown on the screen with the question:

```
                                TOGGLE

Is this the wanted file?        Yes    No
```

Hitting **enter** enables you to change data to the 'new' values, following the procedure of Section 3.3.1. Selecting NO, and hitting **enter** brings you back to the list of general data files.

3.2.4 Select Existing General Data File

CRIWAR enables you to evaluate changes in the irrigation water requirements of an existing irrigated area due to changes in meteo and crop data. To do this, you retrieve an existing general data file. The procedure is:

1 Move to the option **Select Existing General Data File** and hit **enter.**

All the names of general data files will be shown on the screen as follows:

```
Select General Data File
File Name          Date of Creation
etc.
```

2 Use the **arrow** keys to move through the list of files, and
3 Hit **enter** to select the file you want.

The selected file will be shown on the screen with the question:

TOGGLE

Is this the wanted file? **Yes** No

Hitting **enter** retrieves the file. File data are written on the screen for further reference. Selecting NO and hitting **enter** takes you back to the list of general data files.

The file TUNUYAN.GEN, which is an example of a general data file, is included with CRIWAR (Figure 3.2). If, for some reason, no existing file (named *.GEN) is available, the only options you have are to **Create (a) New General Data File** (Section 3.2.1), or to read general data files from a backup disc and then select one of those files.

GENERAL DATA

Country	**Argentina**	
Name of region or project	**Mendoza Province**	
Description of irrigated area	**Chivilcoy Command Area, Tunuyan System**	
Hemisphere	**South**	
Latitude (degrees, minutes)	**33.05**	
Altitude above mean sea level	**653**	m
Size of irrigable area	**1532**	ha
Calculation period:month/10-days	**month**	
Mean depth of water application	**75**	mm per application
Interval between applications	**20**	days

Figure 3.2 Example of a general data file in the manual; TUNUYAN.GEN

3.3 Meteo Data

Before CRIWAR can generate reports or graphs, you have to select a meteo file and a cropping pattern file to work with. If you attempt to select the menu branch **REPORTS/GRAPHS** before you have selected all files, CRIWAR will require you to select the missing files first. Upon entering the **METEO DATA** branch of the menu, you will see the following window:

Create New Meteo File
Edit Existing Meteo File
Select Existing Meteo File

Some example files are included with CRIWAR. If, for some reason, no existing meteo file (named *.MTF) is available, the only options you have are to **Create New Meteo File** (Section 3.3.1), or to read files from a backup disc and then select one of those files.

3.3.1 Create New Meteo File

As already stated, CRIWAR can only calculate the crop irrigation water requirements for a region if data are available on temperature, rainfall, sunshine, average relative humidity, and average wind speed. If there is no meteo file for the region in the directory, you should:

1. Select the **Create New Meteo File** sub-menu option and hit **enter.**
2. Type the name of the new file (up to 8 characters) and hit **enter**.

CRIWAR will now display the following empty table for completion. Please note that the data shown for latitude and altitude were user-entered earlier.

Table 3.1 Meteorological input data

Meteo File: * Latitude: * Altitude: *
Height of wind speed measurements above ground level: 2.00 m

MONTH	Temperature		Precipi-	Sunshine	Humidity		Wind speed	
or	Tmin	Tmax	tation P	hours n	RHmean	RHmax	Mean	Ratio
10 DAYS	°C	°C	mm	h	%	%	m/s	-
.								
.								
.								
.								
.								
.								
.								
.								
.								
.								
.								
.								
.								
. *(maximum 18 lines: 12 months or 2 x 18 10-day periods)*								

*) Selected name and data from General Data File will be shown.

The first column will show either **month** or **10-days**, depending on what you selected in Section 3.2.2. Meteo data have to be entered for the entire irrigation season. However, we recommend to complete the table for the entire year. Default values will be shown for wind speed level and the day/night ratio.

To enter, or change, numerical data in the table:

1. Use the **arrow** keys to highlight the field in which data are to be entered and hit **enter**.
2. Type the data.
3. Then hit the **enter** key to record the information.

Most numerical data have an allowable range of values (see Table 3.2 and bottom of screen). If you input a value that is out of range, CRIWAR will show a warning after you have hit **enter**, and will continue to do so until you either enter a value that is within range, or hit **Esc**. The latter returns the field to the previously saved value.

Table 3.2 Range of values of meteorological input parameters

Description parameter	Range			Dimension
Latitude	0 ≤	Latitude	≤ 66	Degrees N or S
Altitude	-500 ≤	Altitude	≤ 4500	Metres
Height wind speed measured	0 ≤	Height	≤ 15	Metres
Temperature	0 ≤	Temperature	≤ 45	Degrees °C
Precipitation	0 ≤	Precip.	≤ 1000	mm per period
Sunshine hour	0 ≤	Sunshine	≤ 24	Hours per day
Relative humidity	0 ≤	Rhum	≤ 100	Per cent
Wind speed	0 ≤	Wind	≤ 15	Metre per second
Maximum rel. humidity	rhum ≤	Rhmax	≤ 100	Per cent
Wind speed ratio day/night	0 ≤	Ratio	≤ 5	Dimensionless

Besides the more common meteorological input data, CRIWAR needs information on the maximum relative humidity and on the wind speed ratio day/night. If these data are not available, CRIWAR will use the following default values

$$\frac{u_{day}}{u_{night}} = 2.0$$

and

$$RH_{max} = \frac{RH_{mean} + 100}{2}$$

Day-time wind speed is calculated with data on mean wind speed and a day-night wind ratio. How the incoming short-wave radiation is calculated will be explained in Section 5.6.1.

After terminating the input of meteo data, hit **Esc** to return to the main menu. CRIWAR will create and save a meteo file with the name you select (e.g. *.MTF). This short name will be shown on the screen. The short name is used to store all the meteo data in the sub-directory (*.MTF file) while the 'Date of creation' assists you in identifying the file. The file name will be printed in the heading of the meteo table (see Tables 3.1 and 3.3).

If no more meteo data need to be included, you can leave the **Meteo Data** menu by hitting **Esc**. The file name *.MTF will be written on the screen and is available for simulation.

3.3.2 Edit Existing Meteo File

Anywhere in the world, the actual weather pattern can deviate from the average meteo data. When this happens in irrigation districts, however, it can influence the

Table 3.3 Meteorological data, Tunuyan Irrigation Project, Argentina.

Meteo File : **TUNUYAN** Latitude: **33.05 ° South** Altitude: **653** m
Height of wind speed measurements above ground level: **2.0** m

Period	Temperature		Precipi-tation P	Sunshine hours n	Humidity		Windspeed	
	Tmin	Tmax			RHmean	RHmax	mean	ratio
month	°C	°C	mm	h	%	%	m/s	–
January	16.7	32.5	35	10.9	53.0	91.0	2.5	2.0
February	15.9	31.7	19	10.1	58.0	92.0	2.2	2.0
March	13.5	28.8	24	8.6	65.0	93.0	2.0	2.0
April	8.0	23.5	8	7.9	69.0	91.0	1.7	2.0
May	4.5	19.1	10	7.1	68.0	90.0	1.6	2.0
June	1.8	14.8	12	6.5	70.0	86.0	1.7	2.0
July	0.8	15.4	6	6.7	65.0	83.0	1.8	2.0
August	2.7	18.3	6	8.0	52.0	76.0	2.1	2.0
September	5.8	22.1	7	8.2	49.0	73.0	2.5	2.0
October	9.2	24.7	26	9.5	49.0	78.0	2.8	2.0
November	13.1	29.1	24	10.6	50.0	87.0	2.9	2.0
December	15.5	31.5	15	10.9	51.0	89.0	2.6	2.0
Totals:			192					

irrigation water requirements. In such a case, rather than checking the water requirements against a meteo file with average data, you will want to check the water requirements against the actual, or forecast, data. To do so, you **Edit** (an) **Existing Meteo File**. The steps are:

1 Select the **Edit Existing Meteo File** sub-menu option.
2 Hit **enter.**
3 Type name of the new file.
4 Hit **enter**.

All the names of the meteo files will be shown on the screen as follows:

```
═══ Select Meteo File ═══
File Name          Date of Creation
etc.
```

5 Use the **arrow** keys to move through the list of files, and
6 Hit **enter** to copy all data of the selected file to the 'new file'.

You will now be back in the 'old' meteo table with the 'new' file name selected for use. Following the procedure of Section 3.3.1, you can now change the meteo data to the 'new' values.

3.3.3 Select Existing Meteo File

CRIWAR enables you to evaluate changes in the irrigation water requirements as a function of changing cropping patterns while the meteo data remain constant. For

this purpose, you have to retrieve the existing meteo file from the directory. The procedure is:
1 Move to the **Select Existing Meteo File** option and hit **enter.**

All names of meteo data files will be shown on the screen as follows:

Select Meteo File

File Name   Date of Creation
etc.

2 Use the **arrow** keys to move through the list of files, and
3 Hit **enter** to select the data file you want.
The selected file will be shown on the screen with the question:

TOGGLE

Is this the wanted file?   **Yes**   No

Hitting **enter** retrieves the file. File data are written on the screen for further reference. Selecting NO and hitting **enter** takes you back to the list of meteo data files.

Some examples of meteo files are included with CRIWAR. If, for some reason, no existing database file (named *.MTF) is available, the only options you have are to **Create New Meteo File** (Section 3.3.1), or to read meteo files from a backup disc and then select one of those files.

3.4 Cropping Pattern Data

Before CRIWAR can generate reports or graphs, you first have to select a general data file, a meteo file, and a cropping pattern file to work with. If you attempt to select the menu branch **REPORTS/GRAPHS** before these files are selected, CRIWAR will require you to select those files first. Upon entering the **CROP DATA** branch of the menu, you will see the following window on screen:

Select Cropping Pattern File

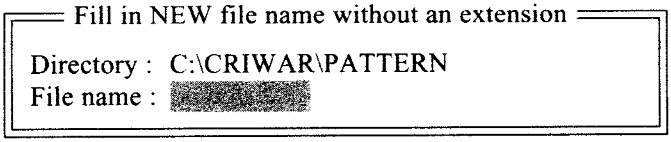
Create New Cropping Pattern File
Edit Existing Cropping Pattern File
Select Existing Cropping Pattern File

A database of example files is included with CRIWAR. If, for some reason, no existing cropping pattern file (named *.PAT) is available, the only options you have are to **Create New Cropping Pattern File**, or to read files from a backup disc and then select one of those files.

3.4.1 Create New Cropping Pattern File

There are many situations where you may want to compose an entirely new cropping pattern. This is particularly true for newly designed irrigation systems. Equally, there are many situations where a calibration is needed, based on the 'as-measured' cropping pattern of an existing irrigated area. What you then need to do is:

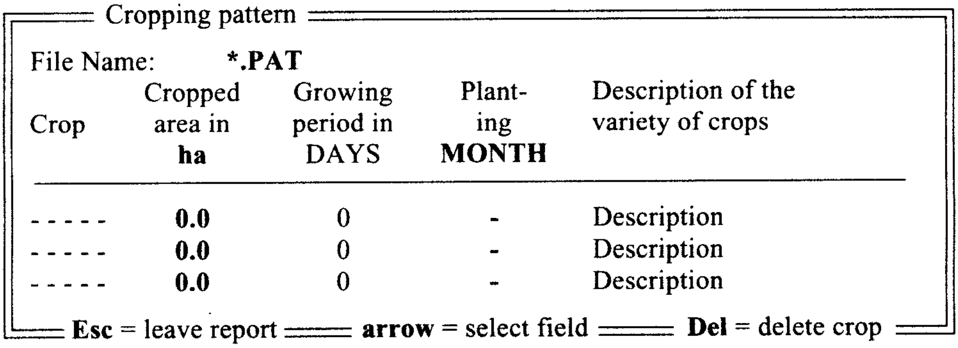
1 Select the **Create New Cropping Pattern File** sub-menu option and hit **enter**. The following window will appear:



Fill in NEW file name without an extension

Directory : C:\CRIWAR\PATTERN
File name :

2 Type name of new cropping pattern file (up to 8 characters) and hit **enter**.



Cropping pattern

File Name: ***.PAT**

Crop	Cropped area in **ha**	Growing period in DAYS	Planting **MONTH**	Description of the variety of crops
- - - - -	**0.0**	0	-	Description
- - - - -	**0.0**	0	-	Description
- - - - -	**0.0**	0	-	Description

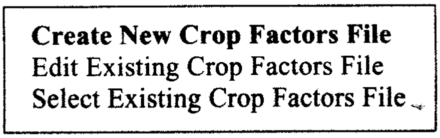
Esc = leave report **arrow** = select field **Del** = delete crop

The file name *.PAT has been user-entered under Step 2 above. The remaining bold printed information in the table heading comes from the pre-selected General Data File.

You can enter the bold fields in the first, second, and fourth column of the table. The recommended procedure to complete this table is:

3 Use the **arrow** keys to select (the first) 'crop' field in the first column, and hit **enter**.

The following crop selection window will be shown:

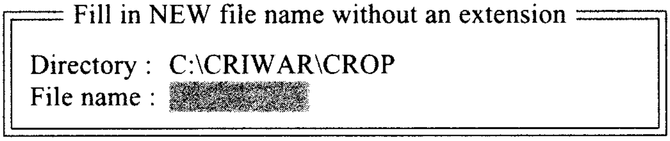


As can be seen, CRIWAR allows you to add (create) a new crop (file) to the cropping pattern, edit the data in an existing user-given crop file, and select a previously created crop file.

Create New Crop Factors File

The procedure to create a new crop file is:

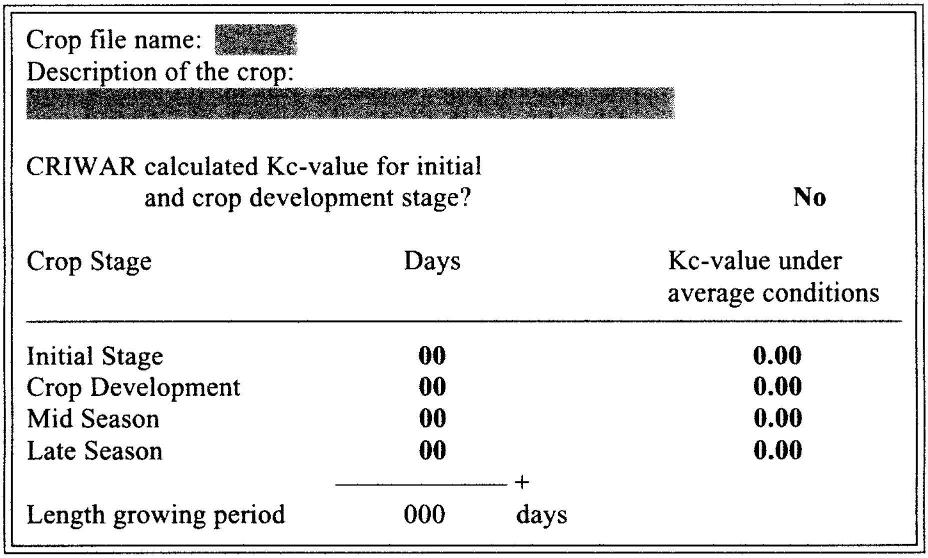
1 Select the **Create New Crop File** sub-menu option and hit **enter**. The following window will appear:



Fill in NEW file name without an extension

Directory : C:\CRIWAR\CROP
File name :

2 Type the name of the new crop file (up to 8 characters) and hit **enter**. As shown below, this crop name is shown in the top line of the crop factors table. In the crops sub-directory, this file will receive an extension .UDC (Users-Defined Crop).



Crop file name:
Description of the crop:

CRIWAR calculated Kc-value for initial and crop development stage? **No**

Crop Stage	Days	Kc-value under average conditions
Initial Stage	**00**	**0.00**
Crop Development	**00**	**0.00**
Mid Season	**00**	**0.00**
Late Season	**00**	**0.00**
	+	
Length growing period	000 days	

3 Type a description of the new crop file (up to 40 characters) and hit **enter**. This description will be shown in the third line of the above table.

The value of the crop coefficient during the crop's initial and development stages can either be calculated by CRIWAR or be user-given (default). If you want CRIWAR to calculate these values:

4 Use the **arrow** keys to select the Yes-No field and hit **enter**.

5 Toggle to YES and hit **enter** again.

The two related k_c fields become inaccessible, and will show the CRIWAR-calculated values. Enter the other values as before. CRIWAR will calculate the total length of the growing period, and will write this length in the third colomn of the cropping pattern table.

After you have entered data in all fields, you can save the file for future use by hitting **Esc**. Information on the crop will be shown in the cropping pattern table. If you hit **Esc** before all fields have been completed, CRIWAR will warn:

> Warning
>
> All crop development stages
> and k_c values must have
> non-zero values.
> Do you want to enter the
> missing data?
>
> Hit **Y**(es) or **N**(o)

Hitting **Y**(es) takes you back to the crop file window for completion. Selecting **N**(o), and hitting **enter**, deletes the non-completed crop file and takes you back to the sub-menu. CRIWAR does not accept incomplete crop files.

Once back in the cropping pattern table (window), you should enter a value for both the cropped area and for the month (or 10-day period) in which the crop is sown or planted. If these values are missing, CRIWAR will disregard this crop in the **REPORT/GRAPH** branch. The procedure for entering the month (or 10-day period) in which the crop is sown or planted is:

1 Select the related line in the table and hit **enter**. You will then see a window listing the 12 months or the 36 10-day periods (Table 3.4)
2 Use the **arrow** keys to select the month or 10-day period and hit **enter**.

Table 3.4 Month and numbering of 10-day periods

Month	Number of 10-day Period		
January	1	2	3
February	4	5	6
March	7	8	9
April	10	11	12
May	13	14	15
June	16	17	18
July	19	20	21
August	22	23	24
September	25	26	27
October	28	29	30
November	31	32	33
December	34	35	36

Please note that CRIWAR keeps track of the calculation period of all cropping pattern files. The calculation period of the meteo file and the cropping pattern file must be the same for CRIWAR to generate output files (reports and graphs).

Edit Existing Crop Factors File

You can add other crops to the cropping pattern by entering the **Edit Existing Crop Factors File** option. Upon hitting **enter**, you have to repeat the above Steps 1, 2, and 3. You are now in the window:

Copy from a CRIWAR-Programmed Crop File?
Copy from a User-Given Crop File?

Entering the first option will give you a list of 50 CRIWAR pre-programmed crops (named *.CRP). You can edit a pre-programmed crop into the cropping pattern by doing the following:

1 Use the **arrow** keys to select a crop and hit **enter**. You will see standard information on the crop you selected, followed by a decision window:

TOGGLE

Is this the wanted file? **Yes** No

If you toggle to **No** and hit **enter**, you will return to the crop selection sub-menu. If you answer **Yes**, the crop information can be edited as explained above.

Please note that an edited crop file becomes a '**user-defined crop**' factors file (named *.UDC). You cannot overwrite a CRIWAR pre-programmed file. You can only delete these protected crop files by using MS-DOS commands. To edit a user-defined crop (factors file) and add it to the cropping pattern, you follow the above procedure. Now, however, you are able to overwrite an existing user-defined crop factors file.

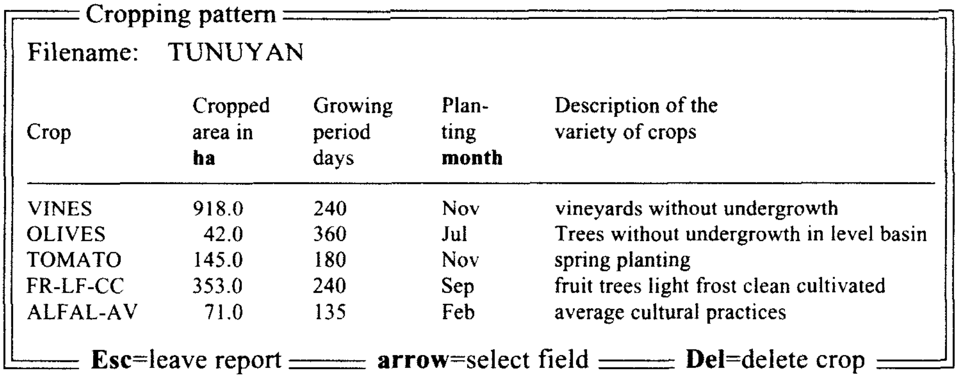
Select Existing Crop Factors File

Upon entering the **Select Existing Crop Factors File** option, you can select and add a crop to the cropping pattern by doing the following:

1 Use the **arrow** keys to select a crop and hit **enter**. The standard information on the crop you selected will be given, followed by the above decision window:

If you toggle to **No** and hit **enter**, you will return to the crop selection sub-menu. If you answer **Yes**, the crop information will be written into the cropping pattern table. Data on the cropped area and the planting month (or 10-day period) should also be entered.

The cropping pattern file (window) will be shown as in the following example:



```
Cropping pattern
Filename:  TUNUYAN

           Cropped    Growing    Plan-      Description of the
Crop       area in    period     ting       variety of crops
           ha         days       month
------------------------------------------------------------------------
VINES      918.0      240        Nov        vineyards without undergrowth
OLIVES      42.0      360        Jul        Trees without undergrowth in level basin
TOMATO     145.0      180        Nov        spring planting
FR-LF-CC   353.0      240        Sep        fruit trees light frost clean cultivated
ALFAL-AV    71.0      135        Feb        average cultural practices
Esc=leave report    arrow=select field    Del=delete crop
```

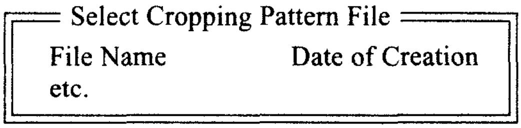
If no more crops need to be included in the cropping pattern, you leave the **CROP DATA** menu by hitting **Esc**. The file name will be shown on the screen.

3.4.2 Edit Existing Cropping Pattern File

In irrigated areas, studies often need to be made of the effect that changes in the cropping pattern will have on the irrigation water requirements. For this purpose, rather than create a new cropping pattern file for the area, you will simply want to modify its existing cropping pattern file. To do so, you **Edit** (data in an) **Existing Cropping Pattern File**, in this case the original cropping pattern. The steps are:

1 Select the **Edit Existing Cropping Pattern File** sub-menu option.
2 Hit **enter**.
3 Type the name of the new cropping pattern file.
4 Hit **enter**.

All names of cropping pattern files in the database will be shown on the screen as follows:

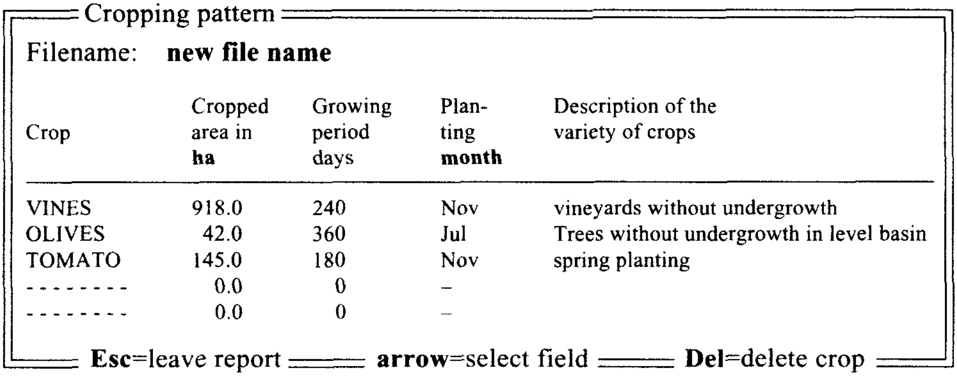


```
Select Cropping Pattern File
File Name            Date of Creation
etc.
```

In a new computing session for the same irrigated area, CRIWAR retrieves this existing cropping pattern file, displays its content, and gives you the option of introducing changes (e.g. delete crops, add crops, change crop specifications and cropped areas).

5 Use the **arrow** keys to move through the list of files, and
6 Hit **enter** to copy all data from the selected file to the 'new' file.

You will now be back in the original cropping pattern with the new file name for use. The new file name *.PAT is shown in the heading of the table.


Cropping pattern

Filename: **new file name**

Crop	Cropped area in **ha**	Growing period days	Plan-ting **month**	Description of the variety of crops
VINES	918.0	240	Nov	vineyards without undergrowth
OLIVES	42.0	360	Jul	Trees without undergrowth in level basin
TOMATO	145.0	180	Nov	spring planting
--------	0.0	0	–	
--------	0.0	0	–	

Esc=leave report **arrow**=select field **Del**=delete crop

To delete a crop from the cropping pattern:

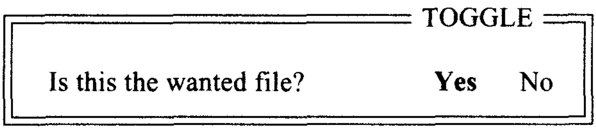
7 Use the **arrow** keys to select the crop you want to delete, and hit **Del**.

To change information on a crop that is already in the crop file, or to add a new crop to the file, use the procedures described in Section 3.4.1.

3.4.3 Select Existing Cropping Pattern File

For any cropping pattern file that has been entered into the database, CRIWAR can generate a new output in combination with a different meteo file. To do this, you have to retrieve the cropping pattern file from the database. The procedure is:

1 Use the **arrow** keys to select a cropping pattern file and hit **enter**. If the calculation period of the selected cropping pattern file is compatible with the current calculation period, the selected cropping pattern table will appear on the screen, followed by a decision window:


TOGGLE

Is this the wanted file? **Yes** No

If you toggle to **No** and hit **enter**, you will return to the **Select Cropping Pattern File** sub-menu. If you answer **Yes**, the file will be retrieved and its name will be written on the screen.

3.5 Summary of Parameter Ranges and Related Warnings

To prevent you from entering erratic or non-realistic data, the parameters in CRIWAR are limited to a certain physical range of values. CRIWAR will warn you if the parameters you enter are out of the related ranges.

3.5.1 Range of Acceptable Values for Parameters

CRIWAR only accepts input parameters that have a numerical value within a pre-programmed range. If you enter an out-of-range value, CRIWAR will show you the relevant range on the screen. You should then select a value that is within the range. Tables 3.5 and 3.6 show the range of values used by CRIWAR and the dimensions of the various numerical parameters.

Table 3.5 Range of values of meteorological input parameters

Description parameter	Range	Dimension
Latitude	$0 \leq$ Latitude ≤ 66	Degrees N or S
Altitude	$-500 \leq$ Altitude ≤ 4500	Metres
Height wind speed measured	$1 \leq$ Height ≤ 15	Metres
Temperature	$0 \leq$ Temperature ≤ 45	Degrees ° C
Precipitation	$0 \leq$ Precip. ≤ 1000	mm per period
Sunshine hour	$0 \leq$ Sunshine ≤ 24	Hours per day
Relative humidity	$0 \leq$ Rhum ≤ 100	Per cent
Wind speed	$0 \leq$ Wind ≤ 15	m/s
Maximum rel. humidity	rhum $\leq$ Rhmax ≤ 100	Per cent
Wind speed ratio day/night	$0 \leq$ Ratio ≤ 5	Dimensionless

Table 3.6 Range of acceptable values for crop input parameters

Description parameter	Range	Dimension
Total cropped area	$0 \leq$ tot.sur. $\leq 1\,000\,000$	ha
Mean application depth	$20 \leq$ depth ≤ 200	mm
Crops in pattern	$1 \leq$ ichois ≤ 40	–
Crop coefficient of user-given crop	$0 \leq k_c \leq 2$	–

Questions that should be answered with either **Yes** or **No**, **North** or **South**, and **10-days** or **Month**, etc., will only accept the relevant answer; no other answer will be accepted. CRIWAR will show the warning 'Incorrect Answer' at the bottom of the screen and will give a beep.

For alpha numerical parameters (name of the region or project, the name of the country), the number of available characters is limited. This limitation is always indicated at the related location.

The names given to database files should not exceed 10 characters, including the file extension (example: TUNUYAN.MTF).

3.5.2 Additional Warnings

CRIWAR can match the calculation period of general data files and meteo files to the same (user selected) calculation period. However, CRIWAR cannot change the calculation period of a cropping pattern file. Hence, you must select a cropping pattern file with a matching calculation period. CRIWAR will show the following error message if a non-matching file is selected:

```
Error

The loaded pattern file
is not compatible with
the selected calculation
period.

Hit any key to continue.
```

Each name of a crop file can be selected only once in the same cropping pattern. Thus, if the selected name (crop) is already included in the cropping pattern, CRIWAR will warn:

```
Warning

This crop is already
included in the cropping pattern.
Choose other crop name or
delete old crop from
cropping pattern.

Hit any key to continue.
```

While the cropping pattern is being composed, CRIWAR will keep track of the total irrigated area per month (or per 10-day period). If this total exceeds the user-given total irrigable area in the selected general data file, CRIWAR will print a warning. If, for example, the irrigable area is overcharged by 3450 ha in June, CRIWAR shows:

```
Warning

The user-given irrigable
area is overcharged by
3450 ha during the
period      JUNE

Hit any key to continue
```

Since no irrigable area remains available to add crops to the cropping pattern, you should review the irrigated area per crop. You can change data by using the above procedure. The shown month (or 10-day period) is the first month during which the irrigable area is overcharged. Following correction, the warning may return for another month.

CRIWAR can calculate the irrigation water requirements of a cropping pattern containing 40 crops. If the 41st crop is selected, CRIWAR shows:

```
──── Warning ──────────────

 The CRIWAR cropping pattern
     is limited to 40 crops.
     This total capacity has
          been used.


   Hit any key to continue
```

Although, during data entry, CRIWAR has checked the number of daily sunshine hours ($n \leq 24$ hours/day), CRIWAR calculates and checks whether the daily number of sunshine hours, n, does not exceed the maximum possible number of sunshine hours, N, at the related latitude.

For example:
For a project at a latitude of 50 degrees north, the user has entered the average daily sunshine as $n = 18.2$ hour a day. CRIWAR compares this average given value with the maximum possible number of sunshine hours, N, at this latitude, which is 8.9 hours a day. While the meteo file was being created, CRIWAR accepted the given input value, because $n = 18.2$ is less than 24 h/day. At this stage, however, during the calculation procedure, CRIWAR gives a warning:

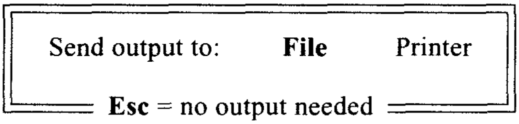
```
──── ERROR ────────────────────────────────

The user-given number of sunshine hours in
meteo file [redacted].MTF in JUNE      is greater
than the possible number of sunshine hours at
the given latitude (N ≤ 8.9 hours per day).
Enter correct data first in the meteo file!

──── Hit any key to continue ──────────────
```

3.6 Printing Files

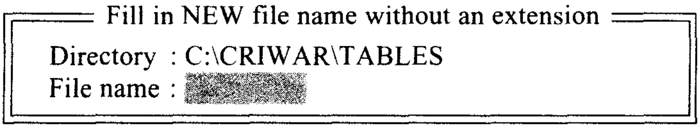
By hitting **F10**, you can print all the files of general data, meteo data, cropping pattern, and crop factor that are on the screen, through either the **Create** or **Edit** sub-menus. Two options are available to handle these files:



Send output to: **File** Printer

Esc = no output needed

- Printer: To send the table to a line printer.
- File: To send the shown table to a file; *.OUT in the \CRIWAR\TABLES sub-directory . The following window will appear:

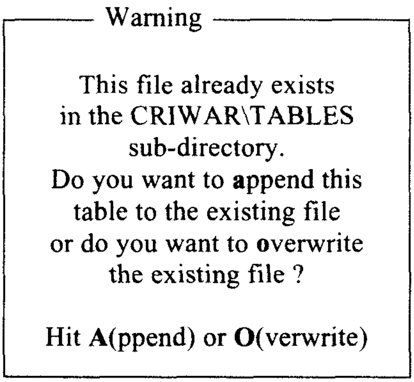


Fill in NEW file name without an extension

Directory : C:\CRIWAR\TABLES

File name :

If the file does not yet exist, typing a file name and hitting **enter** returns you to the sub-menu. If the file name already exists, a warning will be shown:



Warning

This file already exists
in the CRIWAR\TABLES
sub-directory.
Do you want to **a**ppend this
table to the existing file
or do you want to **o**verwrite
the existing file ?

Hit **A**(ppend) or **O**(verwrite)

Further tables can be appended to this same file. So, too, can the output tables under **REPORTS/GRAPHS**. The tables can be printed subsequently through word-processing software.

4 Reports and Graphs

4.1 The Main Menu

The main menu of CRIWAR consists of the five branches shown in Figure 4.1:

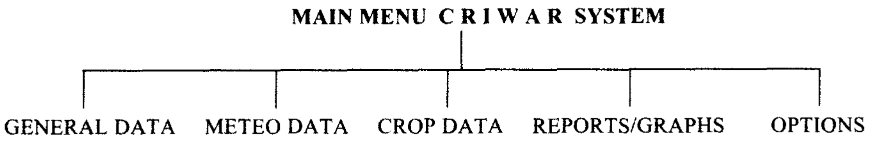


Figure 4.1 The five main branches of the CRIWAR menu

Earlier chapters have explained the **GENERAL DATA, METEO DATA, CROP DATA**, and **OPTIONS** branches. Chapter 4 explains the **REPORTS/GRAPHS** branch.

Before you can enter this branch, you have to select three files: a General Data File, a Meteo Data File, and a Cropping Pattern File. A message will appear on the screen listing the selected files. When you enter the **REPORT/GRAPHS** branch, the following sub-menu becomes available:

Select Method

FAO Modified Penman
Penman-Monteith

After you have entered your choice, the following output sub-menus become available:

Cropping Pattern Report
Reference ET Table
ETp and Pe Tables
Graphs

4.2 Cropping Pattern Reports

How to prepare a cropping pattern file was explained in Section 3.4.1. Upon entering the **Cropping Pattern Report** sub-menu, you can view the following three related output reports:

```
Cropping Pattern Table with Kc Values
Cropping Pattern Bar Chart
Cropping Ratio Table
```

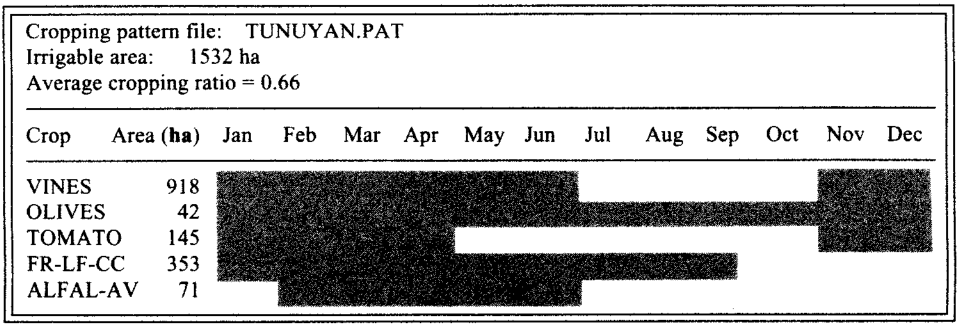
To select one of the alternative reports, use the **arrow** keys and hit **enter**. The report you selected will be displayed. Examples are shown in Tables 4.1, 4.2, and 4.3. The tables may be longer than displayed, but can be viewed with the use of the **arrow** keys.

Table 4.1 Irrigated cropping pattern; Chivilcoy command area, Tunuyan system

```
Cropping pattern file:  TUNUYAN.PAT
Irrigable area:    1532 ha
Frequency of irrigation during initial stage of crop growth:  20 days
Mean depth of irrigation water application: 75  mm per turn
----------------------------------------------------------------------------
                     Crop coefficients, Kc, during growing period
Crop      Area (ha) Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec
----------------------------------------------------------------------------
VINES         918  0.81 0.88 0.88 0.88 0.71 0.57                     0.59 0.69
OLIVES         42  0.85 0.85 0.68 0.58 0.58 0.48 0.60 0.61 0.72 0.72 0.73 0.85
TOMATO        145  0.90 1.15 1.13 0.63                               0.45 0.70
FR-LF-CC      353  0.56 0.75 0.85 0.85 0.85 0.85 0.84 0.70 0.63
ALFAL-AV       71       0.90 0.90 0.90 0.90
```

Tables 4.2 and 4.3 show the average cropping ratio, which is an indicator of the fraction of the irrigable area cropped throughout the year. The cropping ratio is defined as the 12-month-average value of the cropped area over the irrigable area, A_{cr}/A_{ir} (see Table 4.3).

Table 4.2 Cropping pattern bar chart, Chivilcoy command area, Tunuyan system



```
Cropping pattern file:  TUNUYAN.PAT
Irrigable area:    1532 ha
Average cropping ratio = 0.66
----------------------------------------------------------------------------
Crop      Area (ha) Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec
----------------------------------------------------------------------------
VINES         918
OLIVES         42
TOMATO        145
FR-LF-CC      353
ALFAL-AV       71
```

Table 4.3 Cropping Ratio, Chivilcoy, Argentina

Cropping pattern file: TUNUYAN.PAT
Irrigable area: 1532 ha

MONTH	Cropped Area in **ha**	Area Ratio Cropped/Irrigable
January	1458	0.95
February	1529	1.00
March	1529	1.00
April	1529	1.00
May	1384	0.90
June	1313	0.86
July	395	0.26
August	395	0.26
September	395	0.26
October	42	0.03
November	1105	0.72
December	1105	0.72
Average:	1015	0.66

After viewing a report, hitting **Esc** returns you to the next highest menu level. Hitting **F10** brings you to the output options. Two options are available to you:

```
Send output to:      File      Printer

      Esc = no output needed
```

- Printer: Will send the table to a line printer.
- File: Will send the shown table to a file; *.OUT in the \CRIWAR\TABLES sub-directory. The following window will appear:

```
Fill in NEW file name without an extension

Directory :  C:\CRIWAR\TABLES
File name :
```

Typing a file name and hitting **enter** returns you to the sub-menu, provided that the file does not already exist. If the new file name does exist, a warning will be shown:

Warning

This file already exists
in the CRIWAR\TABLES
sub-directory.
Do you want to **append** this
table to the existing file
or do you want to **o**verwrite
the existing file ?

Hit **A**(ppend) or **O**(verwrite)

Further tables can be appended to this same file. The tables can subsequently be printed through word-processing software.

4.3 Tables for the Reference *ET*

As was mentioned in Section 4.1, the reference crop evapotranspiration is determined either by the FAO Modified Penman Method (default) or by the Penman-Monteith Method. At this stage, you have already selected one of these methods.

4.3.1 The FAO Modified Penman Method

In the FAO Modified Penman Method (Doorenbos and Pruitt 1977), the reference surface is defined as:

> *'An extensive surface of 0.08 to 0.15 m tall green grass cover of uniform height, actively growing, completely shading the ground, and not short of water.'*

Consequently, the reference crop evapotranspiration rate, ET_g, in fact represents the potential evapotranspiration rate of grass in Equation 4.1

$$ET_{p,fao} = k_c \, ET_g \tag{4.1}$$

Upon entering the sub-menu option **Reference *ET* Table**, you will see a table as in the following example:

Table 4.4 Reference crop evapotranspiration, ET_g

Based on meteo file: TUNUYAN.MTF
Mendoza Province
Argentina
FAO Modified Penman Method
ET*g* in mm/day and mm/month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mm/day	8.9	7.4	5.2	3.1	2.0	1.5	1.7	3.0	4.6	6.5	8.4	9.0
mm/month	275	208	161	94	62	44	54	92	137	202	252	278

Total ET*g* of the region/project: 1858.3 mm/year

4.3.2 Penman-Monteith Method

Choosing the Penman-Monteith Method means that you will still be using the typical characteristics of a grass cover for the new reference crop. Now, however, the reference crop is an imaginary crop with fixed properties. Standardization of certain parameters in the Penman-Monteith Method has led to the following definition (Smith 1990):

> *'The reference crop evapotranspiration rate, ET_h, is defined as the rate of evapotranspiration from an hypothetical crop with an assumed crop height (0.12 m), and a fixed canopy resistance (70 s/m), and albedo (0.23), which would closely resemble the evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground, and not short of water.'*

Consequently, the reference crop evapotranspiration, ET_h, in fact represents the potential evapotranspiration of the above hypothetical crop in Equation 4.2

$$ET_{p,pm} = k_c \, ET_h \tag{4.2}$$

Upon entering the sub-menu option **Reference *ET* table**, you will see a table as in the following example:

Table 4.5 Reference crop evapotranspiration, ET_h

Based on meteo file: TUNUYAN.MTF
Mendoza Province
Argentina
Penman-Monteith Method
ET*h* in mm/day and mm/month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
mm/day	7.0	6.1	4.5	2.9	1.9	1.4	1.7	2.8	4.1	5.3	6.7	7.1
mm/month	218	170	139	88	60	43	54	86	123	166	200	220

Total ET*h* of the region/project: 1565.5 mm/year

A comparison of the values in Tables 4.4 and 4.5 shows that the reference ET_h is about 15% lower than the ET_g values.

4.4 ET_p and P_e Tables

When you enter the sub-menu option **ET_p and P_e tables**, a menu box appears on the screen showing:

Crop evapotranspiration
Crop irrigation water requirements

To select one of the alternatives, use the **arrow** keys and hit **enter**. The table you selected will be displayed. Examples are shown in Tables 4.6 and 4.7. The tables may be longer than displayed, but you can view them by using the **arrow** keys.

Table 4.6 Potential Crop Evapotranspiration

Mendoza Province , Argentina
Meteo file: TUNUYAN.MTF Cropping pattern file: TUNUYAN.PAT

Crop	ETp in mm/month												ETp in mm/growing period
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
VINES	223	183	141	82	44	25	0	0	0	0	150	192	1041
OLIVES	234	177	110	54	36	21	32	56	98	145	185	237	1385
TOMATO	249	239	182	59	0	0	0	0	0	0	114	195	1037
FR-LF-CC	153	156	136	80	53	37	45	65	86	0	0	0	811
ALFAL-AV	0	187	144	84	56	0	0	0	0	0	0	0	472

The table may be longer than displayed, but you can view it by using the arrow keys.

Table 4.7 Crop irrigation water requirements

File names: TUNUYAN.GEN; TUNUYAN.MTF; TUNUYAN.PAT
Mendoza Province , Argentina
Irrigable area: 1532 ha

MONTH	Total cropped area ha	Total ETp m3 * 10 ^6	Pe m3 * 10 ^6	ETp - Pe m3 * 10 ^6	ETp - Pe mm
Jan	1458	3.050	0.484	2.566	176
Feb	1529	2.783	0.261	2.522	165
Mar	1529	2.189	0.303	1.886	123
Apr	1529	1.205	0.122	1.083	71
May	1384	0.646	0.138	0.508	37
Jun	1313	0.370	0.158	0.213	16
Jul	395	0.174	0.024	0.150	38
Aug	395	0.251	0.024	0.228	58
Sep	395	0.345	0.028	0.317	80
Oct	42	0.061	0.009	0.052	124
Nov	1105	1.618	0.221	1.397	126
Dec	1105	2.145	0.151	1.994	180
Total :		14.838	1.923	12.915	1195

The table may be longer than displayed, but you can view it by using the ***arrow*** *keys.*

Hitting **F10** leads you to the method of output. Hitting **Esc** returns you to the next highest menu level.

4.5 Graphs

The **Graphs** sub-menu allows several calculated parameters to be presented as a function of time (month or 10-days). Entering this sub-menu, you will see:

Modify Specifications
Calculate and Show Results

To select parameters as shown in the window below, you have to enter the **Modify Specifications** branch.

Report specifications

Graph file name: **NEW**

Comment line:

NOTE: Include no more than two parameters in one figure.

Average temperature (°C)	**No**
Precipitation (mm/month)	**No**
Cropped area **A**(cr) (ha)	**No**
Area ratio **A**(cr)/**A**(ir)	**No**
Effective precip. Pe (mm/month)	**No**
ETref (mm/month)	**No**
ETp (mm/month)	**No**
ETp - Pe (mm/month)	**No**
ETp - Pe (m^3/month)	**No**

Note: The units are as selected under the menu branch **OPTIONS**. They can be changed if desired.

Hitting **enter** allows you to type a file name (replacing **new**) which can be saved as c:\criwar\graphs*.pcx. Hitting **enter** again returns you to the sub-menu, provided the file does not yet exist. If it already exists, a warning will be shown. Graphs cannot be appended to this same file.

Warning

This file already exists
in the CRIWAR\GRAPHS
sub-directory.
Do you want to overwrite
the existing file ?

Hit **Y**(es) or **N**(o)

The **down arrow** key will move you to a comment line, where you hit the **enter** key if a comment is to be input. This comment will be printed as a figure caption in the report.

To maintain the readability of graphs, you may print no more than two parameters in each graph. If you want to show more parameters, you can save more graphs using a different file name. You can select the parameters for the graph as follows:

1 Use the **arrow** keys to select the relevant parameter.
2 Hit **enter**. A selection box will appear showing:
3 Toggle yes or no and hit **enter** again.

TOGGLE

Yes

No

4 After the parameters have been set (maximum 2 per graph), hit **Esc** to return to the selection menu.

5 To view the graph on screen; use the **arrow** key to select **calculate and show results** and hit **enter**. An example graph is shown in Figure 4.2.

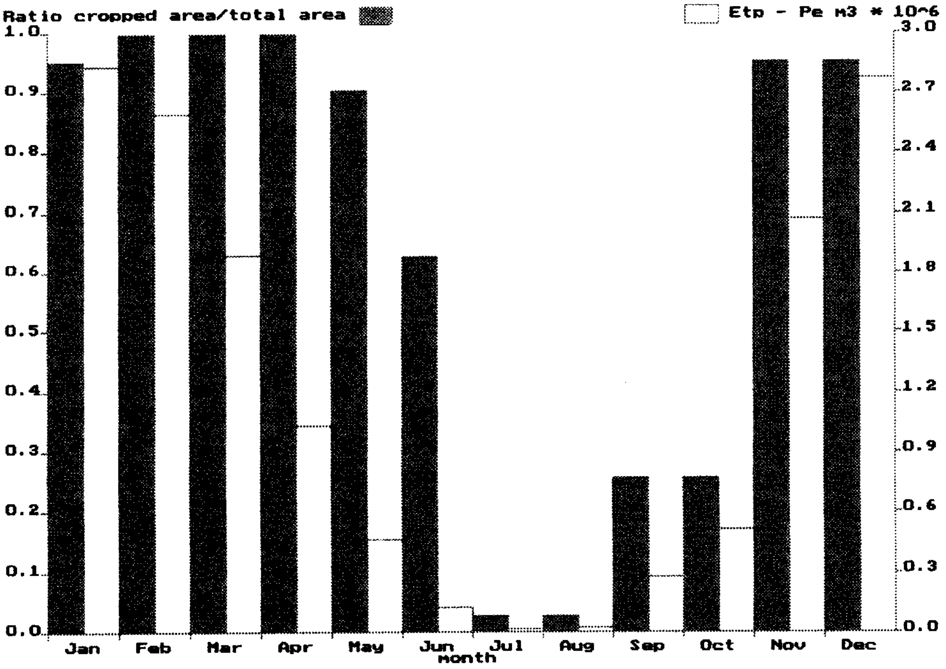


Figure 4.2 Example of a graph

Hitting **F5** saves the above output graph as a *.PCX file in the sub-directory C:\CRIWAR\GRAPHS. This differs from the options for tables. Hitting **Esc** returns you to the next higher menu level without saving the graph. The graphs can subsequently be printed through word-processing software.

Once you have reviewed all the above tables and graphs, you can leave the **REPORTS/GRAPHS** branch of the menu by hitting **Esc**. Once back in the main menu, you can select a different combination of a General Data File, Meteo File, or Cropping Pattern File to work with (by entering the related menu branch), or you can return to MS-DOS (by hitting **Esc**).

5 Theory of Evapotranspiration

5.1 Introduction

Evapotranspiration is an important term in the water balance of an irrigated area. Irrigation engineers want to know how much of the irrigation water that has been supplied is consumed by the crops; only then can they calculate, or estimate, the remaining components of the water balance. Agriculturists, on the other hand, want to know the specific water requirements of a crop so that they can obtain a satisfactory yield; they also want to know whether these water requirements are being met under the prevailing irrigation practices.

Section 5.3 of this chapter presents the theory of Penman's open water evaporation. This is followed by the FAO modification of this theory in Section 5.4, and by the recently accepted Penman-Monteith Method in Section 5.5. How this theory is applied in practice will be explained in Sections 5.6, 5.7, and 5.8.

5.2 Concepts and Developments

In the past, many empirical equations have been developed to estimate the *potential evapotranspiration* (i.e. the evapotranspiration from cropped soils that have an optimum water supply) (Blaney and Criddle 1950; Turc 1954; Jensen and Haise 1963). These empirical correlation methods are often valid only for the local conditions under which they were developed, and as such are hardly transferable to other areas. Nowadays, the focus is therefore on physically-based approaches, which have a wider applicability.

For the process of evapotranspiration, three basic physical requirements in the soil-plant-atmosphere system must be met:

1) A continuous supply of water;
2) Energy to change liquid water into vapour;
3) A vapour gradient to maintain a flux from the evaporating surface to the atmosphere.

The various methods of determining evapotranspiration are based on one or more of these requirements. For example, the soil-water-balance approach is based on 1), the energy-balance approach is based on 2), and the combination method (energy balance plus heat and mass transfer) is based on parts of 2) and 3).

Penman (1948) was the first to introduce the combination method. He estimated the evaporation from an open water surface, and then used that as a reference evaporation. Multiplied by a crop factor, this provided an estimate of the potential evapotranspiration from a cropped surface. Penman's Method requires meteorological data on air temperature, air humidity, solar radiation, and wind speed. Because even this combination method contains a number of empirical relationships, a host of researchers have proposed numerous modifications to adjust it to local conditions.

After analyzing a range of lysimeter data worldwide, Doorenbos and Pruitt (1977) proposed the FAO Modified Penman Method, which has found worldwide application in irrigation and drainage projects. To estimate crop water requirements, CRIWAR uses the same two-step approach as Penman did, but it does not use Penman's open water evaporation, but the evapotranspiration from a reference crop. Hence, CRIWAR estimates a reference evapotranspiration, reads crop coefficients per crop and per growth stage from crop factor files, and then multiplies the two to find the crop water requirements.

For the FAO Modified Penman Method (Doorenbos and Pruitt 1977), the reference crop is defined as:

> *'An extended surface of an 0.08 to 0.15 m tall green grass cover of uniform height, actively growing, completely shading the ground, and not short of water.'*

There was evidence, however, that the Modified Penman Method over-predicted the crop water requirements. Hence, using similar physics as Penman did, Monteith (1965) developed an equation that describes the transpiration from a dry, extensive, horizontal, and uniformly vegetated surface, fully covering the ground, that is optimally supplied with water. In international literature, this equation is known as the Penman-Monteith Equation.

Recent comparative studies (e.g. Jensen et al. 1990) show the convincing performance of the Penman-Monteith approach under varying climatic conditions, thereby confirming the results of many individual studies reported over the past years. An expert consultation on procedures to revise the prediction of crop water requirements was held in Rome (Smith 1990). There, it was agreed to recommend the Penman-Monteith approach as the currently best-performing combination equation. Through the introduction of canopy and air resistances to water vapour diffusion, estimates of potential and actual evapotranspiration would, in principle, be possible with the Penman-Monteith Equation.

Nowadays, this direct, or one-step, approach is increasingly being followed, especially in research environments. Nevertheless, since accepted canopy and air resistances may not yet be known for many crops, the two-step Penman approach (i.e. using crop factors) is still commonly used under field conditions. The reference crop in the Penman-Monteith approach is defined as:

> *'A hypothetical crop fully covering the ground, and not short of water, with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s/m, and a canopy reflection coefficient of 0.23.'*

5.3 Evaporation from Open Water : The Penman Method

As was mentioned earlier, CRIWAR does not use the 'classical' Penman Method

(1948), but instead uses the FAO Modified Penman Method (default) and the 'modern' Penman-Monteith Method. To give our readers a better understanding of the matter, however, we shall explain the original Penman Method.

Penman applied the energy balance of open water at the earth's surface. Equating all incoming and outgoing energy fluxes (Figure 5.1), he obtained

$$R_n - G = H + \lambda E \tag{5.1}$$

where

R_n = energy flux density of net radiation (W/m^2)
H = flux density of sensible heat into the air (W/m^2)
λE = flux density of latent heat into the air (W/m^2)
G = heat flux density into the water body (W/m^2)

The coefficient λ in λE is the latent heat of vaporization of water and E is the vapour flux density (kg/m^{2}s). To convert the above λE (W/m^2) into an equivalent evapo(transpi)ration in units of mm/d, we multiply λE by a factor 0.0353. This factor equals the number of seconds in a day (86 400), divided by the value of λ (2.45×10^6 J/kg at 20°C), whereby we assume a density of water of 1000 kg/m^3. Supposing that R_n and G can be measured, we can calculate E if we know the ratio

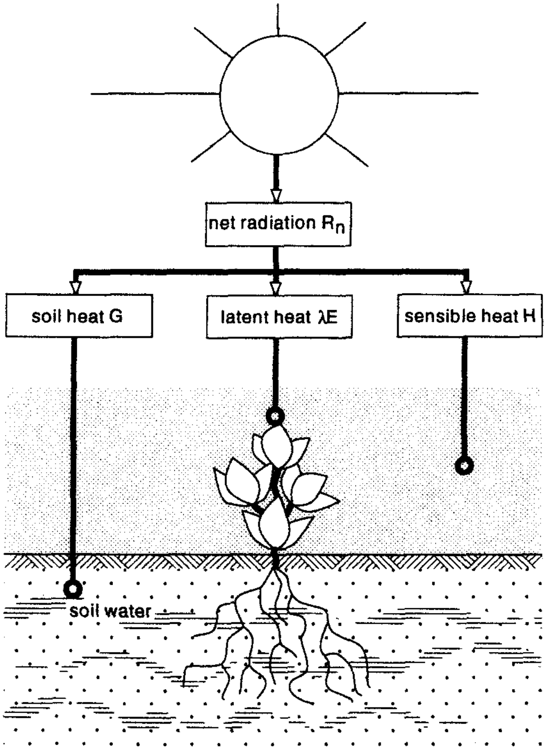


Figure 5.1 Illustrating the variables involved in the energy balance of the soil surface (Feddes and Lenselink 1994)

$H/\lambda E$ (which is called the Bowen Ratio). We can derive this ratio from the transport equations of heat and water vapour in the air.

The situation shown in Figure 5.1 and described by Equation 5.1 shows that radiation energy $(R_n - G)$ is transformed into sensible heat, H, and water vapour, λE, which are transported to the air in accordance with

$$H = \rho_a \, c_p \frac{(T_s - T_z)}{r_a} \tag{5.2}$$

$$\lambda E = \frac{\varepsilon \, \rho_a \, \lambda}{p_a} \frac{(e_{s,sat} - e_z)}{r_a} \tag{5.3}$$

where

c_p = specific heat of dry air at constant pressure (J/kgK)
ε = ratio of molecular masses of water vapour over dry air (–)
p_a = atmospheric pressure (kPa)
ρ_a = density of moist air (kg/m^3)
r_a = aerodynamic diffusion resistance, assumed to be the same for heat and water vapour (s/m)

The other symbols are illustrated in Figure 5.2:

T_s = temperature at the evaporating (water) surface (°C)
T_z = air temperature at a height z above the surface (°C)
$e_{s,sat}$ = saturated vapour pressure at the evaporating (water) surface (kPa)
e_z = prevailing vapour pressure in the external air, measured at the same height as T_z (kPa)

Applying the concept of the similarity of the transport of heat and of water vapour yields the Bowen Ratio

$$\beta = \frac{H}{\lambda E} = \frac{c_p \, p_a}{\lambda \, \varepsilon} \frac{T_s - T_z}{e_{s,sat} - e_z} \tag{5.4}$$

where the ratio $c_p \, p_a / \lambda \, \varepsilon$ is commonly replaced by γ, being the psychrometric constant (kPa/°C).

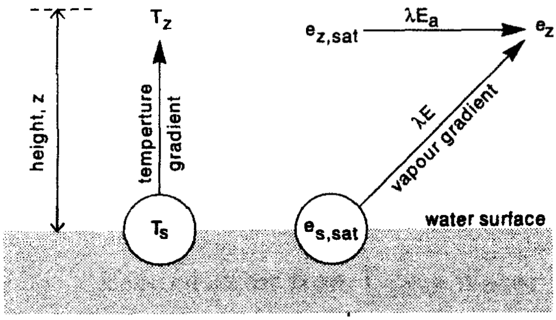


Figure 5.2 Illustration of terminology

The problem with the above equations is that the surface temperature, T_s, is not known (not measurable). Penman therefore took three intermediate steps:

a) He introduced the proportionality constant

$$\Delta = \frac{e_{s,sat} - e_{z,sat}}{T_s - T_z} \tag{5.5}$$

The proportionality constant Δ (kPa/°C) is the first derivative of the function $e_{z,sat}$ versus T_z, known as the saturated vapour pressure curve (Figure 5.3). Note that $e_{s,sat}$ in Equation 5.5 is the saturated vapour pressure at the surface at temperature T_z. Hence

$$\Delta = \frac{de_z}{dT_z} \approx \frac{e_{s,sat} - e_{z,sat}}{T_s - T_z} \tag{5.6}$$

Substituting Equation 5.6 into Equation 5.4 yields

$$\beta = \frac{H}{\lambda E} = \frac{\gamma}{\Delta} \; \frac{e_{s,sat} - e_{z,sat}}{e_{s,sat} - e_z} \tag{5.7}$$

b) He replaced the vapour pressure gradient $e_{s,sat}$ - $e_{z,sat}$ in Equation 5.7 with

$$(e_{s,sat} - e_z) - (e_{z,sat} - e_z)$$

This gives

$$\beta = \frac{\gamma}{\Delta}\left(1 - \frac{e_{z,sat} - e_z}{e_{s,sat} - e_z}\right) \tag{5.8}$$

c) He introduced the 'adiabatic vapour transport' in such a way that, under isothermal conditions (i.e. no heat is added to or removed from the system), we

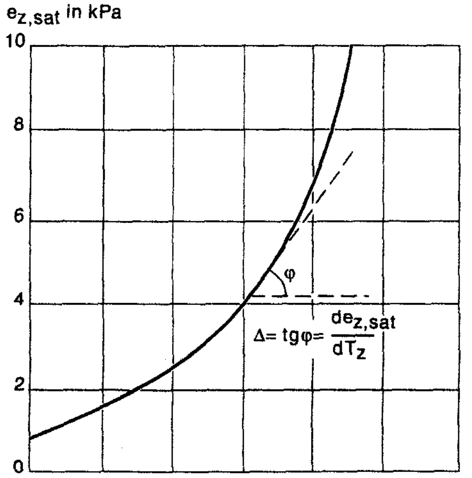


Figure 5.3 Saturated water vapour pressure, $e_{z,sat}$, as a function of air temperature, T_z (Feddes and Lenselink 1994)

can assume that $e_{s,sat} \approx e_{z,sat}$. If we introduce this assumption into Equation 5.3, the theoretical adiabatic evaporation, λE_a, equals

$$\lambda E_a = \frac{\varepsilon \, \rho_a \, \lambda}{p_a} \, \frac{e_{z,sat} - e_z}{r_a} \tag{5.9}$$

A comparison of this equation with Equation 5.3 shows that

$$\frac{e_{z,sat} - e_z}{e_{s,sat} - e_z} = \frac{E_a}{E} \tag{5.10}$$

so that

$$\beta = \frac{\gamma}{\Delta} (1 - \frac{E_a}{E}) \tag{5.11}$$

Substituting the above information into Equation 5.1, and writing E_o (subscript *o* denoting open water) for *E* yields the Penman Formula, which is

$$E_o = \frac{\Delta}{\Delta + \gamma} \, \frac{R_n - G}{\lambda} + \frac{\gamma}{\Delta + \gamma} E_a \tag{5.12}$$

where, as defined above:

E_o = open water evaporation rate (kg/m^2 s)
Δ = proportionality constant de_z/dT_z (kPa/°C)
R_n = net radiation flux density (W/m^2)
G = heat flux density into the water body (W/m^2)
λ = latent heat of vaporization (J/kg)
γ = psychrometric constant (kPa/°C)
E_a = isothermal evaporation rate (kg/m^2 s)

Equation 5.12 shows the combination of two processes in one equation. The first term is the evaporation equivalent of the net flux of radiant energy to the surface, also called the 'radiation term'. The second term quantifies the corresponding aerodynamic process of water-vapour transport from the evaporating water surface to the surrounding air, also called the 'aerodynamic term'.

For open water, the heat flux into the water is often ignored, especially over longer periods (hence $G \approx 0$). Note that the resulting E_o (kg/m^{2}s) should be multiplied by 86 400 seconds to give the equivalent evaporation rate E_o in mm/d.

As was mentioned in Section 5.2, the original Penman Formula (Equation 5.12) used E_o as reference evaporation. The practical value of estimating E_o with Equation 5.12, however, is generally limited to large water bodies (e.g. lakes and flooded rice fields in the very early stages of growth). But, as was also mentioned earlier, CRIWAR does not use Equation 5.12.

5.4 The FAO Modified Penman Method

5.4.1 The Modification

The modification of the Penman Method, as introduced by Doorenbos and Pruitt (1977), started from the assumption that evapotranspiration from grass largely occurs in response to climatic conditions. Because short grass is the common surrounding of agro-meteorological stations, they suggested that, instead of using evaporation from open water as a reference, the evapotranspiration from grass, 0.08 to 0.15 m tall and not short of water, be used. The main changes in Penman's Formula to compute this reference evapotranspiration, ET_g, relate to:

- The short-wave reflection coefficient (approximately 0.05 for water and 0.25 for grass);
- A more sensitive wind function in the aerodynamic term; and
- An adjustment factor to take into account that local climatic conditions deviate from an assumed standard. This adjustment is needed to allow various combinations of radiation, relative humidity, and day/night wind ratio. CRIWAR uses the adjustment factors of Section 5.4.2.

If the heat flux, G, is set equal to zero for daily periods, the Modified Penman Equation can be written as

$$ET_g = c\left[\frac{\Delta}{\Delta + \gamma} \times 86400\,\frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma}\,2.7\,f(u)\,(e_{z,sat} - e_z)\right] \tag{5.13}$$

where

ET_g = reference crop evapotranspiration rate (mm/d)
c = dimensionless adjustment factor (see Section 5.4.2)
R_n = energy flux density of net incoming radiation (W/m^2)
$f(u)$ = wind function; $f(u) = 1 + 0.864u_2$
u_2 = wind speed measured at 2.0 m above ground surface (m/s)
$e_{z,sat}-e_z$ = vapour pressure deficit (kPa)
Δ, γ = as defined earlier

Potential evapotranspiration rate from a cropped surface is subsequently found by multiplying this reference ET_g by the appropriate crop coefficient (Section 5.7).

5.4.2 The Adjustment Factor, *c*

If the average climatological conditions for which the (Modified) Penman Formula was developed are not met, the adjustment factor in Equation 5.13 differs from 1.0. The values of the adjustment factor, c, can be estimated from comparisons of calculated and measured values of ET_g, whereby the interactions between wind speed, relative humidity, and solar radiation are analyzed. Table 5.1 gives values of c as a function of the day-time wind speed, u_{day}, the ratio of day over night wind speed, (u_{day}/u_{night}), the maximum relative humidity, RH_{max}, and the solar radiation, R_s. CRIWAR calculates the values of c by interpolation from Table 5.1.

Table 5.1 Adjustment factor, c, as a function of the maximum relative humidity, RH_{max}, incoming shortwave radiation, R_s, day-time wind speed, u_{day}, and the wind speed ratio, u_{day}/u_{night} (Doorenbos and Pruitt 1977)

	$RHmax = 30\%$				$RHmax = 60\%$				$RHmax = 90\%$			
R_s [mm/d] →	3	6	9	12	3	6	9	12	3	6	9	12
u_{day} [m/s]	$u_{day}/u_{night} = 4.0$											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.79	.84	.92	.97	.92	1.00	1.11	1.19	.99	1.10	1.27	1.32
6	.68	.77	.87	.93	.85	.96	1.11	1.19	.94	1.10	1.26	1.33
9	.55	.65	.78	.90	.76	.88	1.02	1.14	.88	1.01	1.16	1.27
	$u_{day}/u_{night} = 3.0$											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.76	.81	.88	.94	.87	.96	1.06	1.12	.94	1.04	1.18	1.28
6	.61	.68	.81	.88	.77	.88	1.02	1.10	.86	1.01	1.15	1.22
9	.46	.56	.72	.82	.67	.79	.88	1.05	.78	.92	1.06	1.18
	$u_{day}/u_{night} = 2.0$											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.69	.76	.85	.92	.83	.91	.99	1.05	.89	.98	1.10	1.14
6	.53	.61	.74	.84	.70	.80	.94	1.02	.79	.92	1.05	1.12
9	.37	.48	.65	.76	.59	.70	.84	.95	.71	.81	.96	1.06
	$u_{day}/u_{night} = 1.0$											
0	.86	.90	1.00	1.00	.96	.98	1.05	1.05	1.02	1.06	1.10	1.10
3	.64	.71	.82	.89	.78	.86	.94	.99	.85	.92	1.01	1.05
6	.43	.53	.68	.79	.62	.70	.84	.93	.72	.82	.95	1.00
9	.27	.41	.59	.70	.50	.60	.75	.87	.62	.72	.87	.96

Data need to be supplied on the day-night ratio of the wind speed and on the maximum relative humidity (see Section 3.3). However, if these data are not available, CRIWAR will use the following default values:

$$u_{day}/u_{night} = 2.0$$

and

$$RH_{max} = (RH + 100)/2$$

where RH is the average relative humidity. Day-time wind speed is calculated from data on mean wind speed and a day-night wind ratio. How to calculate the incoming short-wave radiation flux density will be explained in Section 5.6.

5.5 The Penman-Monteith Approach

5.5.1 Crops with Full Soil Cover

In analogy with Section 5.4, the evapotranspiration from a wet crop can be described by an equation very similar to Equation 5.13. Nevertheless, we have to take into account the differences between a grassed surface and a hypothetical crop surface. In this context, these differences are:

- The albedo (or reflection coefficient for solar radiation) is different for the hypothetical crop surface (0.23) and a grassed surface (0.25).
- The hypothetical crop surface has a roughness (dependent on crop height and wind speed), and hence an aerodynamic resistance, r_a, which differs considerably from that of a grassed surface. This results in a different wind function.
- A stomatal diffusion resistance is added, resulting to a modification of the psychrometric constant, γ.

Following the same reasoning that led to Equation 5.9, we can write the isothermal evaporation rate, E_a, for a wet crop as

$$E_a = \frac{\varepsilon\ \rho_a}{p_a}\ \frac{(e_{z,sat} - e_z)}{r_a} \tag{5.14}$$

From the discussion by De Bruin (1982) of Monteith's concept of a dry vegetated surface, we can treat the dry vegetation layer as if it were one big leaf. The actual transpiration process (liquid water changing into vapour) takes place in cavities below the stomata of this 'big leaf', and the air within these cavities will be saturated (pressure $e_{s,sat}$) at leaf temperature, T_s (Figure 5.4). Water vapour escapes through the stomata to the outer 'leaf' surface, where a certain lower vapour pressure reigns. It is assumed that this lower vapour pressure at leaf temperature, T_s, equals the saturated vapour pressure, $e_{z,sat}$, at air temperature, T_z. During this diffusion, a 'big leaf' stomatal resistance, r_c, is encountered. As the vapour subsequently moves from the leaf surface to the external air, where actual vapour pressure, e_z, is present, an aerodynamic resistance is encountered. When the vapour diffusion rate through the stomata equals the vapour transport rate into the external air, we can write

$$E_a = \frac{\varepsilon\rho_a}{p_a}\ \frac{e_{s,sat} - e_{z,sat}}{r_c} = \frac{\varepsilon\rho_a}{p_a}\ \frac{e_{z,sat} - e_z}{r_a} = \frac{\varepsilon\rho_a}{p_a}\ \frac{e_{s,sat} - e_z}{r_c + r_a} \tag{5.15}$$

From Equation 5.15, it follows that a dry cropped surface can be described by the same equation as a wet cropped surface if the vapour pressure difference ($e_{z,sat}$ - e_z) in Equation 5.14 is replaced by

$$e_{z,sat} - e_z = \frac{e_{s,sat} - e_z}{1 + \dfrac{r_c}{r_a}} \tag{5.16}$$

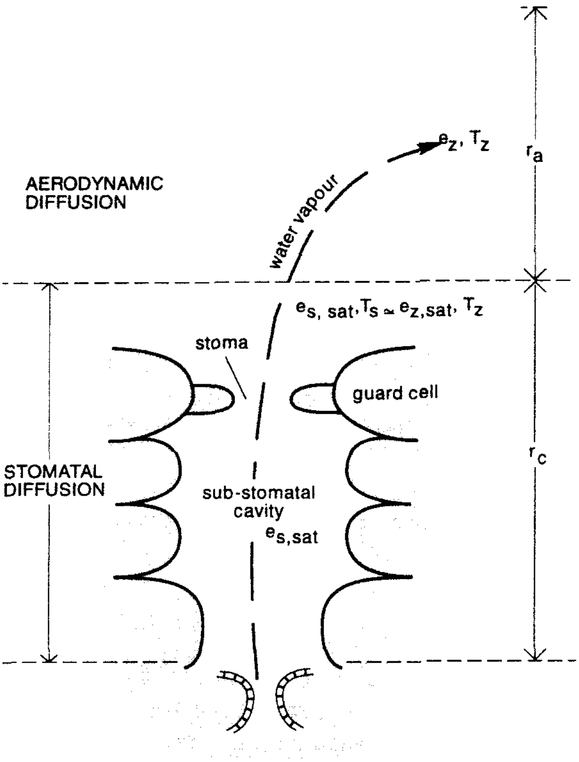


Figure 5.4 The path of water vapour through a leaf stoma, showing relevant vapour pressures, temperatures, and resistances (Feddes and Lenselink 1994)

According to Monteith (1965), the same effect is obtained by multiplying γ in Penman's Equation by $(1 + r_c/r_a)$. The equation of Penman-Monteith for a dry vegetation, completely shading the ground, then reads

$$ET_h = \frac{\Delta}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \frac{R_n - G}{\lambda} + \frac{c_p \, \rho_a}{\lambda[\Delta + \gamma(1 + \frac{r_c}{r_a})]} \frac{e_{z,sat} - e_z}{r_a} \tag{5.17}$$

where, as defined earlier

ET_h = reference evapotranspiration rate from a dry crop surface (kg/m^2 s)
c_p = specific heat of dry air at constant pressure (J/kgK)
$e_{z,sat}$ = saturated vapour pressure at temperature T_z (kPa)
e_z = prevailing vapour pressure in the external air, at the same height as T_z is measured (kPa)
r_a = aerodynamic diffusion resistance, assumed to be the same for heat and water vapour (s/m)
r_c = 'big leaf' stomatal diffusion resistance (s/m)
Δ = proportionality constant $de_{air,sat}/dT_{air}$ (kPa/°C)
R_n = net radiation flux density (W/m^2)
G = heat flux density into the soil (W/m^2)

ρ_a = density of moist air (kg/m^3)
λ = latent heat of vaporization (J/kg)
γ = psychrometric constant (kPa/°C)

The ET_h value of Equation 5.17 should be multiplied by 86400 seconds to give the equivalent reference crop evapotranspiration rate in mm/day.

5.5.2 Canopy Resistance

Equation 5.17 is, in principle, not able to quantify evapotranspiration from partly cropped surfaces. With a partly cropped surface, the evaporation from the soil may become dominant. It appears that the canopy resistance, r_c, of a dry crop completely covering the ground has a non-zero minimum value if the water supply in the rootzone is optimal (i.e. under conditions of potential evapotranspiration). For arable crops, this minimum amounts to r_c = 30 s/m; that of a forest is about 150 s/m.

The canopy resistance is a complex function of incoming solar radiation, water vapour deficit, and soil water content. The relationship between r_c and these environmental quantities varies from crop to crop and also depends on the soil type. It is not possible to measure r_c directly. It is usually determined experimentally with the Penman-Monteith Equation, where ET_h is measured independently (e.g. by the soil-water balance or by a micro-meteorological approach). With that approach, however, the aerodynamic resistance, r_a, has to be known. Owing to the crude description of the vegetation layer, this quantity is poorly defined. Because, in real vegetation, pronounced temperature gradients occur, it is very difficult to determine T_s precisely. In various published studies, r_a is determined very crudely. This implies that some of these published r_c values are inaccurate (de Bruin 1982).

Alternatively, r_c is sometimes related to the single-leaf resistances as measured with a porometer, and to the leaf area index, A_i, as follows

$$r_c = \frac{r_{leaf}}{0.5\,A_i} \tag{5.18}$$

If data on r_{leaf} and A_i are not available, a rough indication of r_c can be obtained by taking r_{leaf} to be 100 s/m. CRIWAR uses a fixed value of r_c = 70 s/m (Section 5.2).

5.5.3 Aerodynamic Resistance

The aerodynamic resistance, r_a, can be quantified by

$$r_a = \frac{\ln\left(\frac{z-d}{z_{om}}\right)\,\ln\left(\frac{z-d}{z_{ov}}\right)}{K^2\,u_z} \tag{5.19}$$

where
z = height at which wind speed is measured (m)

d = displacement height because of crop height (m)
z_{om} = roughness length for momentum (m)
z_{ov} = roughness length for water vapour (m)
K = von Kármán constant (–); equals 0.41
u_z = wind speed measured at height z (m/s)

Equation 5.19 shows that the wind speed, u, increases logarithmically with height, z. It is thus important to know at which height above ground level the wind speed is measured (default height in CRIWAR is 2.0 m). The crop canopy, however, shifts the horizontal asymptote at height z_0 upwards over a displacement height, d, and u_z becomes zero at a height $d + z_0$ (Figure 5.5).

Displacement d depends on the crop height h and is often estimated as

$$d = 0.67h$$

while

$$z_{om} = 0.123h$$

and

$$z_{ov} = 0.1z_{om}$$

In practice, Equation 5.17 is often used to calculate the reference evapotranspiration, ET_h, using the above fixed value of r_c and the relevant value of r_a. For the standard measuring height of $z = 2.0$ m, a hypothetical crop height of 0.12 m, and the above approximations for d, z_{om} and z_{ov}, Equation 5.19 gives $r_a = 208/u_2$.

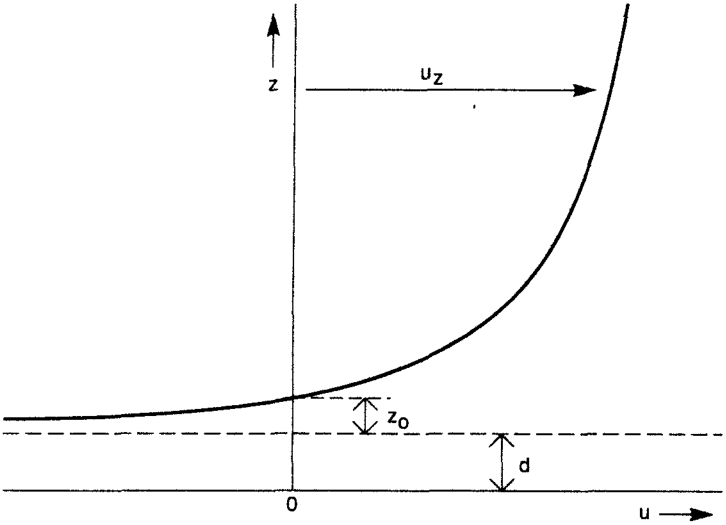


Figure 5.5 The aerodynamic wind profile, illustrating the displacement thickness, d, and the roughness length, z_o

5.5.4 Discussion

As was mentioned in Section 5.2, there was evidence that the Modified Penman Method predicted a higher reference *ET* than the Penman-Monteith Approach. With monthly average meteorological data from 20 stations, ET_g and ET_h were calculated with Equations 5.13 and 5.17, respectively. A plot of the results in Figure 5.6 shows $ET_h = 0.85ET_g$.

5.6 Computing the Reference Evapotranspiration

Accepting the definition of the reference crop as given in Section 5.1, we can find the reference evapotranspiration from Equations 5.13 and 5.17, respectively. These

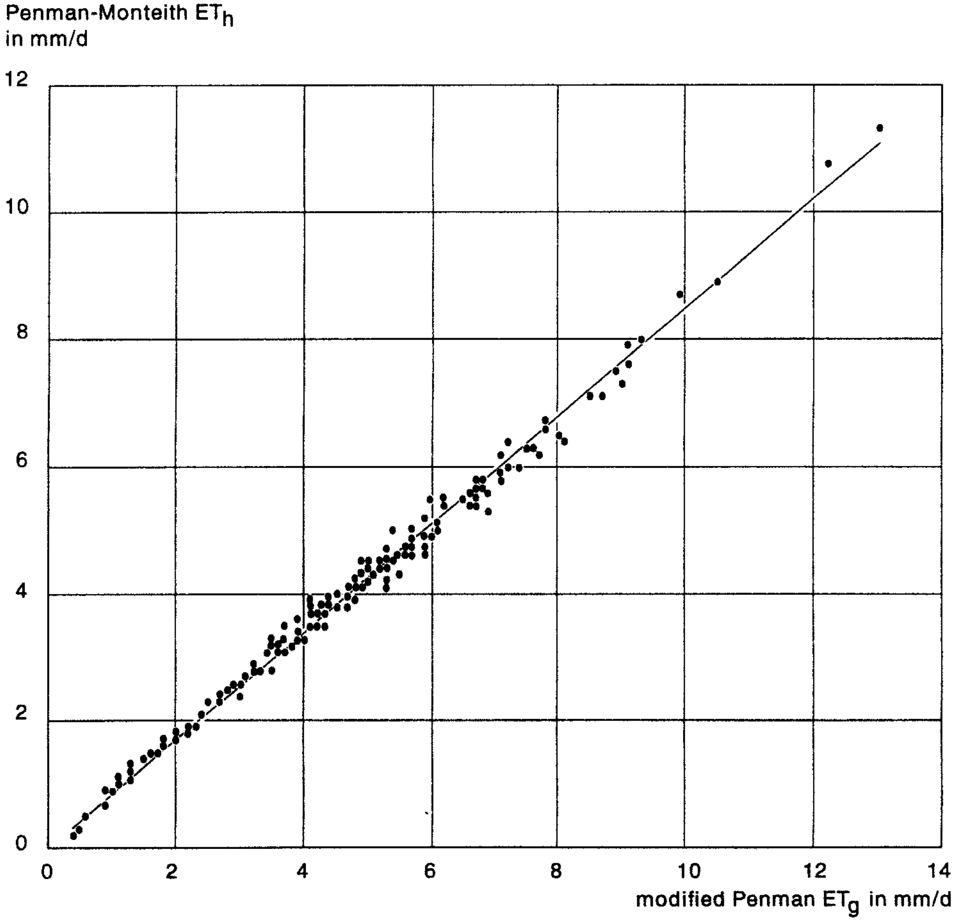


Figure 5.6 Comparison of the reference *ET* for 20 locations, computed with the Modified Penman Method (Equation 5.13) and the Penman-Monteith Approach (Equation 5.17)

equations contain a number of variables that depend on user-given input information from the CRIWAR General Data and Meteo Data files.

5.6.1 CRIWAR Calculations

Psychrometric Constant

The psychrometric constant is defined as

$$\gamma = \frac{c_p\, p_a}{\varepsilon\, \lambda} = 0.00659 p_a \tag{5.20}$$

where

p_a = atmospheric pressure (kPa)
λ = latent heat of vaporization (CRIWAR uses 2.45 x 10^6 J/kg)
c_p = specific heat of dry air at constant pressure (1004.6 J/kgK)
ε = ratio of molar masses of water vapour over dry air (0.622)

Atmospheric Pressure

The atmospheric pressure is related to altitude as follows

$$p_a = 101.3 \left(\frac{T_{av} + 273.16 - 0.0065 H}{T_{av} + 273.16} \right)^{5.256} \tag{5.21}$$

where

H = the altitude above mean sea level (m)
T_{av} = average air temperature (°C); $T_{av} = (T_{max} + T_{min})/2$

Slope of the Vapour Pressure Curve

The slope of the vapour pressure curve, $\Delta = de_{air,sat}/dT_{air}$, is quantified by

$$\Delta = \frac{4098\, \mathrm{e}_{\mathrm{z,sat,av}}}{(\mathrm{T}_{\mathrm{av}} + 237.3)^2} \tag{5.22}$$

The average value of the saturated vapour pressure, $e_{z,sat,av}$, is calculated in a different way with the Modified Penman Method than with the Penman-Monteith Approach. With the Modified Penman Method, the temperature is averaged first, and

$$e_{z,sat,av} = 0.6108 \exp \left(\frac{17.27\, T_{av}}{T_{av} + 237.3} \right) \tag{5.23}$$

With the Penman-Monteith Approach the averaging procedure differs; the value of $e_{z,sat}$ is calculated first with the above equation at both T_{min} and T_{max}. Then the $e_{z,sat,av}$ is calculated by

$$e_{z,sat,av} = \frac{e_{z,sat,Tmin} + e_{z,sat,Tmax}}{2} \tag{5.24}$$

Using data of various meteorological stations, it can be shown that this different Penman-Monteith approach results in about 8% lower reference evapotranspiration.

Net Radiation

Net radiation consists of two parts: net short-wave radiation and net long-wave radiation: $R_n = R_{ns} - R_{nl}$. Net short-wave radiation can be described by

$$R_{ns} = (1 - \alpha)R_s \tag{5.25}$$

where

R_{ns} = net short-wave radiation (W/m^2)
α = albedo, or canopy reflection coefficient (–); a value of 0.23 is used for the Penman-Monteith reference crop; the modified Penman Method uses 0.25
R_s = incoming solar radiation (W/m^2)

The net long-wave radiation is represented by

$$R_{nl} = (0.9\frac{n}{N} + 0.1)\,(0.34 - 0.139\sqrt{e_z}\,)\,\sigma\,\frac{(TK^4_{\max} + TK^4_{\min})}{2} \tag{5.26}$$

where

R_{nl} = net long-wave radiation (W/m^2)
n = daily duration of bright sunshine (h)
N = day length (h)
e_z = actual vapour pressure (kPa)
TK_{max} = maximum absolute temperature (°K)
TK_{min} = minimum absolute temperature (°K)
σ = Stefan-Boltzmann constant (equals 5.6745×10^{-8} W/m^2 K^4)

Actual Vapour Pressure

For the FAO Modified Penman Method, the actual vapour pressure, e_z, is found from

$$e_z = \frac{RH}{100}\, e_{z,sat} \tag{5.27}$$

where RH is the average relative humidity percentage. As stated earlier, the Penman-Monteith Approach uses a different averaging procedure. Hence

$$e_z = \frac{RH}{\dfrac{50}{e_{z,sat,Tmin}} + \dfrac{50}{e_{z,sat,Tmax}}} \tag{5.28}$$

Aerodynamic Evaporation Equivalent

The Penman-Monteith Approach uses the aerodynamic evaporation equivalent. This was defined as (Equation 5.14)

$$E_a = \frac{\varepsilon\, \rho_a}{p_a}\,\frac{e_{z,sat} - e_z}{r_a} \tag{5.29}$$

For the ratio of the molecular masses of water vapour and dry air, a value of $\varepsilon = 0.622$ is used. The density of moist air can be expressed as

$$\rho_a = \frac{p_a}{0.287\,(T_a + 273)} \tag{5.30}$$

in which 0.287 replaces R_a, being the specific gas constant for dry air (0.287 kJ/kg °K), and where the 'officially' needed value for the virtual temperature has been replaced by the absolute temperature (T_{av} + 273).

We can find r_a from Equation 5.21 by substituting the standard measuring height of z = 2.0 m and the reference crop height of 0.12 m, which gives $r_a = 208/u_2$. Substituting the above values into Equation 5.29 and multiplication with 86400 seconds gives (in mm/day)

$$E_a = \frac{900}{(T_{av} + 273)} u_2 \, (e_{z,sat} - e_z) \tag{5.31}$$

Solar Radiation

Many agro-meterological stations do not have a solarimeter to record the solar radiation, but they do have a Campbell-Stokes sunshine recorder to record the duration of bright sunshine. In that case, R_s is estimated by CRIWAR from

$$R_s = (a + b \frac{n}{N}) \, R_A \tag{5.32}$$

where

R_s = solar radiation (W/m^2)
a = fraction of extra-terrestrial radiation on overcast days (–)
$a + b$ = fraction of extra-terrestrial radiation on clear days (–)
R_A = extra-terrestrial radiation, or Angot value (W/m^2)
n = duration of bright sunshine (h)
N = day length (h)

Although a distinction can be made between arid, humid tropical, and other climates, reasonable estimate values of a and b for average climatic conditions are $a = 0.25$ and $b = 0.50$ (CRIWAR used values).

The day length, N, and the extra-terrestrial radiation, R_A, are astronomical values that can be approximated with the following equations

$$R_A = 435 \, d_r \, (\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin \omega_s) \tag{5.33}$$

where

d_r = relative distance between the earth and the sun (-)
ω_s = sunset hour angle (rad)
δ = declination of the sun (rad)
φ = latitude (rad); northern latitude positive; southern negative

The value 435 is used in the Penman-Monteith Method. In the Modified Penman Method, this value is somewhat lower because a lower value was used for the sun constant. The old sun constant was 1353 W/m^2; the new value is 1367 W/m^2. Hence, for the Modified Penman Method, CRIWAR uses (1353/1367) × 435 = 430.7.

The relative distance between the earth and the sun, d_r, is found from

$$d_r = 1 + 0.033 \cos \frac{2\pi J}{365} \tag{5.34}$$

where J is the Julian day, or day of the year (J = 1 for January 1). For monthly values, J can be found as the integer value of $30.42 \times M - 15.23$, where M is the number of the month (1 to 12).

The declination, δ, is calculated from

$$\delta = 0.4093 \sin (2\pi \frac{J + 284}{365}) \tag{5.35}$$

The sunset-hour angle is found from

$$\omega_s = arccos(-tan\varphi \, tan\delta) \tag{5.36}$$

The maximum possible sunshine hours, or the day length, N, can be found from

$$N = \frac{24}{\pi \, \omega_s} \tag{5.37}$$

5.7 Estimating Potential Evapotranspiration

To estimate crop water requirements, CRIWAR relates the potential ET_p of the crop under consideration to an estimated reference evapotranspiration, ET_{ref} (either ET_g or ET_h), by means of a crop coefficient, k_c, as follows

$$ET_p = k_c \, ET_{ref} \tag{5.38}$$

Smith (1990) concluded that the practical crop coefficients, as introduced by Doorenbos and Pruitt (1977), are not only valid if used in combination with ET_g (Modified Penman Method), but also if used with the Penman-Monteith approach, i.e. in combination with ET_h.

5.8 Standard Estimates of Crop Coefficients

A number of CRIWAR crop files show k_c-values as a function of the crop development stage (Section 3.4.1). The four different stages of crop development which are considered for field and vegetable crops are:

1 Initial growth
Germination and early growth of the crop; during this stage, the soil surface is not, or is hardly, covered by the crop canopy (ground cover less than 10%).

2 Crop development
From the end of the initial stage until the attainment of effective full ground cover (between 70 and 80%). Please note that this does not mean that the crop has reached its mature height.

3 Mid-season
From the attainment of effective full ground cover to the start of maturing of the crop. Maturing may be indicated by leaves discoloring (beans) or leaves falling off (cotton). For some crops, this stage may last till very near harvest (sugar beet) unless irrigation is ommited at late season and a reduction in ET_p is induced to increase yield and/or quality (sugarcane, cotton, some grains). Normally this stage lasts well past the flowering stage of annual crops.

4 Late season
From the end of the mid-season stage until full maturity or harvest of the crop.

5.8.1 Initial Growth Stage

During the initial growth stage, the value of the crop coefficient, $k_{c,I}$, depends largely on the level of ET_{ref} and on the frequency with which the soil is wetted by rain or irrigation. Figure 5.7 shows the relationship between $k_{c,I}$, ET_{ref}, and the average interval between irrigation turns or significant rain. Generally, there are two methods of calculating $k_{c,I}$. One is based on the assumption that irrigation water is applied only if soil water content is insufficient to ensure potential transpiration (ideal irrigation regime). The second method, by which $k_{c,I}$ values are taken directly from Figure 5.7, is recommended for use when the interval between irrigation turns

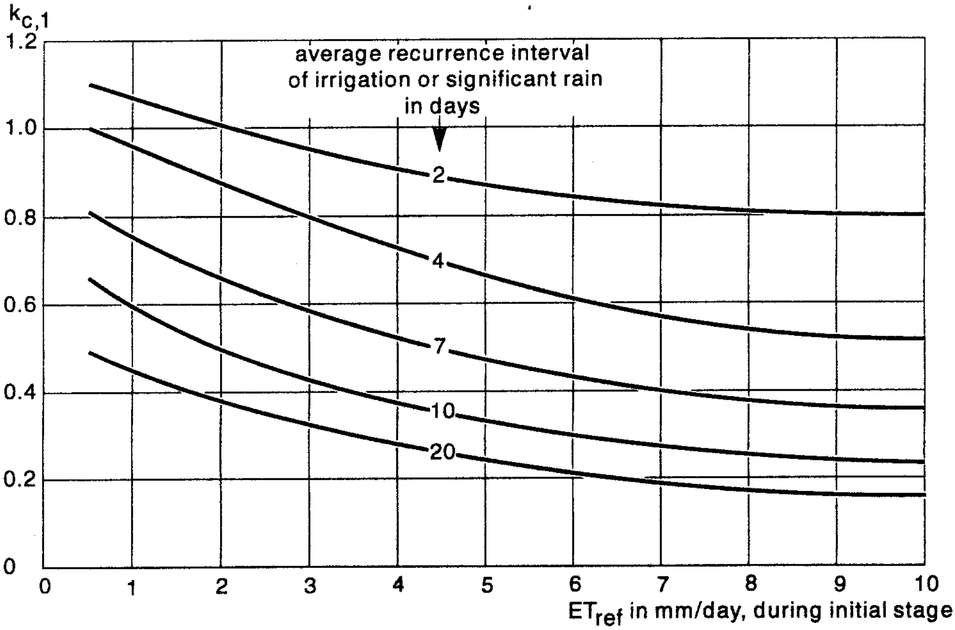


Figure 5.7 Average $k_{c,I}$-value for the initial crop development stage as a function of ET_{ref} and the frequency of irrigation and significant rainfall (Doorenbos and Pruitt 1977)

(or significant rain) is irregular. As the latter is often true in irrigation practice, CRIWAR uses the second method. Depending on the choice of the user, CRIWAR will calculate either ET_g or ET_h. The frequency of irrigation and/or significant rainfall has to be given by the user (Section 3.2).

5.8.2 Other Growth Stages

As soon as the crop gives effective full soil cover (as at the start of the mid-season growth stage), soil evaporation will be negligible. Values for the crop coefficients $k_{c,3}$ (mid-season stage) and $k_{c,4}$ (late season stage) are based on field research. Recommended values are given in Table 5.2. To be able to select the proper values of $k_{c,3}$ and $k_{c,4}$, CRIWAR uses user-given meteo data (relative humidity and wind speed).

Crop coefficients are generally derived from fields with different local conditions and different agricultural practices. These local effects may include: size of fields, advection, irrigation and cultivation practices, climatological variations with time, latitude, altitude, and soil water availability. One should therefore always be careful in applying crop coefficients from experimental data.

When the $k_{c,3}$- and $k_{c,4}$-values are known, and the $k_{c,1}$-value has been calculated, they can be schematized as shown in Figure 5.8. During the crop development stage, a straight line interpolation is assumed to find the $k_{c,2}$-value. The above procedure is used by CRIWAR to calculate the k_c-value at any time during the growing season. The broken line in Figure 5.8 is assumed to approximate the actual k_c-values during the growing season. Of the dates t_1 through t_5, as shown in Figure

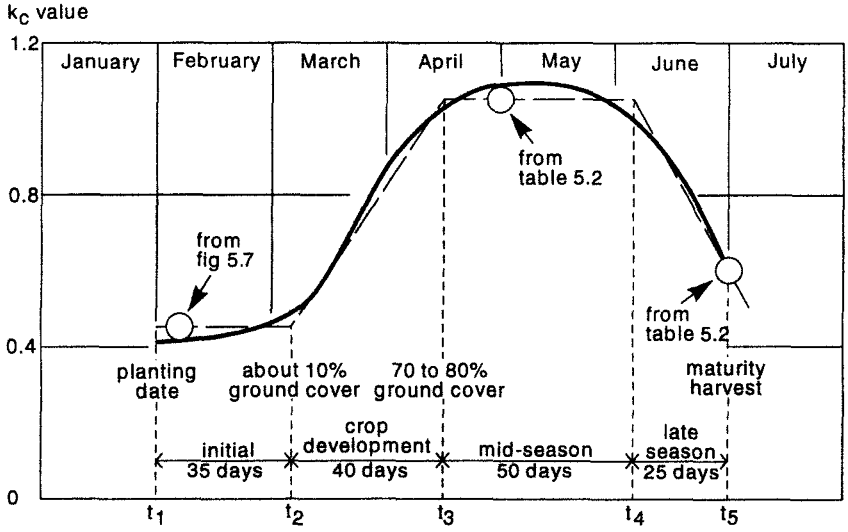


Figure 5.8 Example of the crop coefficient curve for the CRIWAR pre-programmed crop: Tomato

5.8, the user only needs to give the t_l (planting or sowing date). CRIWAR calculates the remaining dates.

As mentioned in Section 5.8, the above procedure applies to the pre-programmed field and vegetable crops.

Table 5.2 Crop coefficients $k_{c,3}$ and $k_{c,4}$ for CRIWAR pre-programmed field and vegetable crops for different stages of crop growth and prevailing climatic conditions. (Doorenbos and Pruitt 1977)

	Humidity		$RH_{min} > 70\%$		$RH_{min} < 20\ \%$	
CROP	Wind speed m/s	STAGE	0-5	5-8	0-5	5-8
Artichokes	Mid-season:	3	0.95	0.95	1.00	1.05
	Harvest or maturity:	4	0.90	0.90	0.95	1.00
Barley		3	1.05	1.10	1.15	1.20
		4	0.25	0.25	0.20	0.20
Beans (green)		3	0.95	0.95	1.00	1.05
		4	0.85	0.85	0.90	0.90
Corn (sweet)		3	1.05	1.10	1.15	1.20
		4	0.95	1.00	1.05	1.10
Corn (grain)		3	1.05	1.10	1.15	1.20
		4	0.55	0.55	0.60	0.60
Cotton		3	1.05	1.15	1.20	1.25
		4	0.65	0.65	0.65	0.70
Onion (dry)		3	0.95	0.95	1.05	1.10
		4	0.75	0.75	0.80	0.85
(green)		3	0.95	0.95	1.00	1.05
		4	0.95	0.95	1.00	1.05
Potato		3	1.05	1.10	1.15	1.20
		4	0.70	0.70	0.75	0.75
Soybeans		3	1.00	1.05	1.10	1.15
		4	0.45	0.45	0.45	0.45
Sugar beet		3	1.05	1.10	1.15	1.20
		4	0.90	0.95	1.00	1.00
	No irrigation during last month	4	0.60	0.60	0.60	0.60
Tomato		3	1.05	1.10	1.20	1.25
		4	0.60	0.60	0.65	0.65
Wheat		3	1.05	1.10	1.15	1.20
		4	0.25	0.25	0.20	0.20

5.8.3 Other Crops

Alfalfa, Grasses, Clover, and Pasture

The k_c-values of this group of crops shows the same variation as the above field crops. However, since the harvest is repeated several times a year, the growth cycle initial ⇒ harvest is passed through several times. For individual fields, this repeated growth cycle has a considerable effect on the irrigation water requirements. In a larger irrigated area, however, not all fields will be harvested on the same date. In such cases, we use the average k_c-values shown in Table 5.3. The values listed are for dry soil conditions; under wet conditions, we recommend increasing the values by 30%.

Table 5.3 k_c-values for alfalfa, clover, grasses, and pasture (Doorenbos and Pruitt 1977)

		Alfalfa	Grass for hay	Clover, Grass-legumes	Pasture
Humid Light to moderate wind	k_c mean	0.85	0.8	1.0	0.95
	k_c peak	1.05	1.05	1.05	1.05
	k_c low*)	0.5	0.6	0.55	0.55
Dry Light to moderate wind	k_c mean	0.95	0.9	1.05	1.0
	k_c peak	1.15	1.1	1.15	1.1
	k_c low*)	0.4	0.55	0.55	0.5
Strong wind	k_c mean	1.05	1.0	1.1	1.05
	k_c peak	1.25	0.15	1.2	1.15
	k_c low*)	0.3	0.5	0.55	0.5

*) k_c mean represents the mean value between cuttings; k_c low, just after cutting
k_c peak, just before harvest

Bananas

The k_c-values for bananas are given in Table 5.4 as a function of climate. For a Mediterranean climate, Table 5.4 assumes planting in March of the first year and the removal of original large leaves in February of the next year. Values may differ with local farm practices. The months refer to the northern hemisphere; for the southern hemisphere, the dates should be shifted 6 months.

In a tropical climate, planting may be in any month. Hence, the k_c-values are given for the month after planting. Also here, the lower k_c-values after about 10 months relate to the decline in active leaf area.

Citrus

Table 5.5 gives k_c-values for large mature trees as a function of ground cover and weed control. For young orchards, the values related to 20 or 50% ground cover should be used. As above, the months refer to the northern hemisphere.

Deciduous Fruits and Nuts

Values of k_c for deciduous fruit and walnut trees are presented in Table 5.6 as a

Table 5.4 k_c values for bananas (Doorenbos and Pruitt 1977)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mediterranean climate												
First-year crop, based on March planting with crop height 3.5 m by August:												
Humid, light to mod. wind	–	–	.65	.6	.55	.6	.7	.85	.95	1.0	1.0	1.0
Humid, strong wind	–	–	.65	.6	.55	.6	.75	.9	1.0	1.05	1.05	1.05
Dry, light to mod. wind	–	–	.5	.45	.5	.6	.75	.95	1.1	1.15	1.1	1.1
Dry, strong wind	–	–	.5	.45	.5	.65	.8	1.0	1.15	1.2	1.15	1.15
Second season with the removal of original plants in February and 80% ground cover by August:												
Humid, light to mod. wind	1.0	.8	.75	.7	.7	.75	.9	1.05	1.05	1.05	1.0	1.0
Humid, strong wind	1.05	.8	.75	.7	.7	.8	.95	1.1	1.1	1.1	1.05	1.05
Dry, light to mod. wind	1.1	.7	.75	.7	.75	.85	1.05	1.2	1.2	1.2	1.15	1.15
Dry, strong wind	1.15	.7	.75	.7	.75	.9	1.1	1.25	1.25	1.25	1.2	1.2

Tropical climate Months following planting	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	.4	.4	.45	.5	.6	.7	.85	1.0	1.1	1.1	.9	.8	.8	.95	1.05
			Suckering					Shooting				Harvest			

Table 5.5 k_c-values for citrus, grown in predominantly dry areas with light to moderate wind (Doorenbos and Pruitt 1977)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Large mature trees providing tree ground cover ≈ **70%**												
Clean cultivated	.75	.75	.7	.7	.7	.65	.65	.65	.65	.7	.7	.7
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing tree ground cover ≈ **50%**												
Clean cultivated	.65	.65	.6	.6	.6	.55	.55	.55	.55	.55	.6	.6
No weed control	.9	.9	.85	.85	.85	.85	.85	.85	.85	.85	.85	.85
Trees providing tree ground cover ≈ **20%**												
Clean cultivated	.55	.55	.5	.5	.5	.45	.45	.45	.45	.45	.5	.5
No weed control	1.0	1.0	.95	.95	.95	.95	.95	.95	.95	.95	.95	.95

function of farm practices and climate. The following notes relate to this table:

*) The k_c-values need to be increased if frequent rain occurs (see Figure 5.7 for adjustments). For young orchards with tree ground cover of 20 and 50%, reduce the mid-season k_c-values by 10 to 15% and 5 to 10%, respectively.

**) The k_c-values in this part of the table assume infrequent wetting by irrigation or rain (every 2 to 4 weeks). In the case of frequent irrigation for March, April, and November, adjust, using Figure 5.7; for May to October, use k_c-values of this table 'with ground cover crop'. For young orchards with tree ground cover of 20

Table 5.6 k_c-values for fully grown deciduous fruit and nut trees (Doorenbos and Pruitt 1977)

	With ground cover crop*)									Without ground cover crop**)								
	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
COLD WINTER WITH KILLING FROST: GROUND COVER STARTING IN APRIL																		
Apples, cherries																		
Humid, light to mod. wind	–	.5	.75	1.0	1.1	1.1	1.1	.85	–	–	.45	.55	.75	.85	.85	.8	.6	–
Humid, strong wind	–	.5	.75	1.1	1.2	1.2	1.15	.9	–	–	.45	.55	.8	.9	.9	.85	.65	–
Dry, light to mod. wind	–	.45	.85	1.15	1.25	1.25	1.2	.95	–	–	.4	.6	.85	1.0	1.0	.95	.7	–
Dry, strong wind	–	.45	.85	1.2	1.35	1.35	1.25	1.0	–	–	.4	.65	.9	1.05	1.05	1.0	.75	–
Peaches, apricots, pears, plums																		
Humid, light to mod. wind	–	.5	.7	.9	1.0	1.0	.95	.75	–	–	.45	.5	.65	.75	.75	.7	.55	–
Humid, strong wind	–	.5	.7	1.0	1.05	1.1	1.0	.8	–	–	.45	.55	.7	.8	.8	.75	.6	–
Dry, light to mod. wind	–	.45	.8	1.05	1.15	1.15	1.1	.85	–	–	.4	.55	.75	.9	.9	.7	.65	–
Dry, strong wind	–	.45	.8	1.1	1.2	1.2	1.15	.9	–	–	.4	.6	.8	.95	.95	.9	.65	–
COLD WINTER WITH LIGHT FROST: NO DORMANCY IN GRASS COVER CROPS																		
Apples, cherries, walnuts*)**																		
Humid, light to mod. wind	.8	.9	1.0	1.1	1.1	1.1	1.05	.85	.8	.6	.7	.8	.85	.85	.8	.8	.75	.65
Humid, strong wind	.8	.95	1.1	1.15	1.2	1.2	1.15	.9	.8	.6	.75	.85	.9	.9	.85	.8	.8	.7
Dry, light to mod. wind	.85	1.0	1.15	1.25	1.25	1.25	1.2	.95	.85	.5	.74	.95	1.0	1.0	.95	.9	.85	.7
Dry, strong wind	.85	1.05	1.2	1.35	1.35	1.35	1.25	1.0	.85	.5	.8	1.0	1.05	1.05	1.0	.95	.9	.75
Peaches, apricots, pears, plums, almonds, pecans																		
Humid, light to mod. wind	.8	.85	.9	1.0	1.0	1.0	.95	.8	.8	.55	.7	.75	.8	.8	.7	.7	.65	.55
Humid, strong wind	.8	.9	.95	1.0	1.15	1.1	1.0	.85	.8	.55	.7	.75	.8	.8	.8	.75	.7	.6
Dry, light to mod. wind	.85	.95	1.05	1.15	1.15	1.15	1.1	.9	.85	.5	.7	.85	.9	.9	.9	.8	.75	.65
Dry, strong wind	.85	1.0	1.1	1.2	1.2	1.2	1.15	.95	.85	.5	.75	.9	.95	.95	.95	.85	.8	.7

and 50%, reduce the mid-season k_c-values by 25 to 35% and 10 to 15%, respectively.

***) For walnuts from March to May, k_c-values are possibly 10 to 20% lower because of slower leaf growth.

Grapes

The k_c-value for grapes varies considerably with farm practices (row spacing, pruning, height and span of trellising) and with cultivation practices.

Table 5.7 gives k_c-values for grapes as a function of climate and ground cover. The months refer to the northern hemisphere.

Table 5.7 k_c-values for grapes; clean cultivated, infrequent irrigation, soil surface dry most of the time (Doorenbos and Pruitt 1977)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Mature grapes grown in areas with killing frost; initial leaves early May, harvest mid-September; ground cover 40-50% at mid-season												
Humid, light to mod. wind	–	–	–	–	.5	.65	.75	.8	.75	.65	–	–
Humid, strong wind	–	–	–	–	.5	.7	.8	.85	.8	.7	–	–
Dry, light to mod. wind	–	–	–	–	.45	.7	.85	.9	.85	.7	–	–
Dry, strong wind	–	–	–	–	.5	.75	.9	.95	.9	.75	–	–
Mature grapes in areas with only light frosts; initial leaves early April, harvest late August to early September; ground cover 30-35% at mid-season												
Humid, light to mod. wind	–	–	–	.5	.55	.6	.6	.6	.6	.5	.4	–
Humid, strong wind	–	–	–	.5	.55	.65	.65	.65	.65	.55	.4	–
Dry, light to mod. wind	–	–	–	.45	.6	.7	.7	.7	.7	.6	.35	–
Dry, strong wind	–	–	–	.45	.65	.75	.75	.75	.75	.65	.35	–
Mature grapes grown in hot dry areas; initial leaves late February-early March, harvest late half of July; ground cover 30-35% at mid-season												
Dry, light to mod. wind	–	–	.25	.45	.6	.7	.7	.65	.55	.45	.35	–
Dry, strong wind	–	–	.25	.45	.65	.75	.75	.7	.55	.45	.35	–

Rice

To estimate the k_c-value for rice, and to determine the related crop development stages, the user needs information on the geographical location (Table 5.8). If, during the dry season, the minimum relative humidity exceeds 70%, the k_c-values given for the wet season are used. No difference is assumed between broadcast/sown and transplanted rice, since the percentage of ground cover during the first month after transplantation differs little from that of broadcast rice.

Note: For upland rice, the same coefficients as given in Table 5.8 for paddy rice can be used because recommended cultivation practice involves maintaining the top soil close to saturation. Only during the initial crop stage should the $k_{c,1}$-values be reduced by 15 - 20%. (This can be done when rice is treated as a user-given crop).

Table 5.8 k_c-values for rice as used in CRIWAR. When $RH_{min} > 70\%$, wet season k_c-values are used (Doorenbos and Pruit 1974).

	Planting	Harvest	First & second month	Mid-season	Last 4 weeks
Humid Asia					
Wet season (monsoon)	June-July	Nov-Dec			
Light to mod. wind			1.1	1.05	.95
Strong wind			1.15	1.1	1.0
Dry season	Dec-Jan	mid May			
Light to mod. wind			1.1	1.25	1.0
Strong wind			1.15	1.35	1.05
North Australia					
Wet season	Dec-Jan	Apr-May			
Light to mod. wind			1.1	1.05	.95
Strong wind			1.15	1.1	1.0
South Australia					
Dry summer	Oct	March			
Light to mod. wind			1.1	1.25	1.0
Strong wind			1.15	1.35	1.05
Humid S. America					
Wet season	Nov-Dec	Apr-May			
Light to mod. wind			1.1	1.05	.95
Strong wind			1.15	1.1	1.0
Europe (Spain, S. France and Italy)					
Dry season	May-June	Sept-Oct			
Light to mod. wind			1.1	1.2	.95
Strong wind			1.15	1.3	1.0
U.S.A.					
Wet summer (south)	May	Sept-Oct			
Light to mod. wind			1.1	1.1	.95
Strong wind			1.15	1.15	1.0
Dry summer (Calif.)	early May	early Oct			
Light to mod. wind			1.1	1.25	1.0
Strong wind			1.15	1.35	1.05

Sugarcane

The crop coefficients for sugarcane vary considerably with climate and cane variety. The total length of the growing season depends on the climate and on the start of the growth period and whether we consider a virgin crop or a ratoon crop. For virgin plantings, this length may be 13 to 14 months in hot Iran, 16 months in Mauritius, and up to 24 months in Hawaii. Ratoon growing periods are shorter: 9 months in Iran, 12 months in Mauritius, and up to 14 months in Hawaii.

Table 5.9 gives k_c-values for an average 12-month ratoon crop and a 24-month virgin crop. The application of irrigation water usually stops between 4 to 6 weeks before harvest.

Table 5.9 k_c-values for sugarcane (Doorenbos and Pruitt 1977)

Crop age			$RH_{min} > 70\%$		$RH_{min} < 20\%$	
12 month	24 month	Growth stage	Light to mod. wind	Strong wind	Light to mod. wind	Strong wind
0 - 1	0 - 2.5	Planting to 0.25 full canopy	.55	.6	.4	.45
1 - 2	2.5 - 3.5	0.25-0.5 full canopy	.8	.85	.75	.8
2 - 2.5	3.5 - 4.5	0.5-0.75 full canopy	.9	.95	.95	1.0
2.5 - 4	4.5 - 6	0.75 to full canopy	1.0	1.1	1.1	1.2
4 -10	6 -17	Peak use	1.05	1.15	1.25	1.3
10 -11	17 -22	Early senescence	.8	.85	.95	1.05
11 -12	22 -24	Ripening	.6	.65	.7	.75

5.8.4 Procedure to Determine Crop Coefficients per Month

If the calculation period for CRIWAR is a month (or 10-day period), k_c- values must be available per month (or 10-day period). Because the crop growing period does not usually coincide with the calendar months, CRIWAR calculates average k_c-values. In the following example, a tomato crop is cultivated with planting date 1 February and harvest date 30 June.

From local experiments (or literature), the duration of the growth stages with corresponding crop coefficients, k_c, of this tomato crop are shown in Table 5.10. Table 5.10 shows that the months and the growth stages do not correspond. Because the user-selected calculation period for ET_p is a month, the k_c of each growth stage has to be transferred to a crop coefficient per calender month. The CRIWAR procedure is as follows:

- February is entirely within the initial stage. Thus
  $k_{c,feb} = 0.45$;
- In March, there are 5 days with $k_c = 0.45$ (initial stage), and 25 days with $k_c = 0.75$ (crop-development stage). Thus,
  $k_{c,mar} = (5/30) \times 0.45 + (25/30) \times 0.75 = 0.70$
  (All months are assumed to have 30 days.);
- In April, there are 15 days with $k_c = 0.75$ (crop-development stage) and 15 days with $k_c = 1.05$ (mid-season stage). Thus
  $k_{c,apr} = (15/30) \times 0.75 + (15/30) \times 1.05 = 0.90$.

Table 5.10 Published k_c-values of an example tomato crop

Growth stage of crop	Duration	Period	k_c
Initial stage	35 days	1 Feb - 5 Mar	0.45
Crop-development stage	40 days	6 Mar - 15 Apr	0.75
Mid-season stage	50 days	16 Apr - 5 Jun	1.05
Late-season stage	25 days	6 Jun - 30 Jun	0.60

- May is completely within the mid-season stage. Hence, $k_{c,may} = 1.05$;
- In June, there are 5 days with $k_c = 1.05$ (mid-season stage) and 25 days with $k_c = 0.60$ (late-season stage). Thus, for June, $k_{c,jun} = (5/30) \times 1.05 + (25/30) \times 0.60 = 0.68$ (rounded off).

The k_c-values of Table 5.11 are thus used for the crop 'tomato':

Table 5.11 Monthly k_c-values for the 'tomato' example crop

	Feb	Mar	Apr	May	Jun
k_c-value calculated by CRIWAR	0.45	0.70	0.90	1.05	0.68

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6 Effective Precipitation

6.1 Introduction

To estimate the irrigation water requirements, we need to know how much of the soil water in the crop's rootzone will be provided by natural precipitation. Hence, precipitation needs to be measured (Figure 6.1). Not all precipitation infiltrates into the soil; a part may evaporate; another part may become surface runoff. Of the precipitation that infiltrates, only a part will be stored in the rootzone; the remainder will recharge the groundwater. Again, only a fraction of the total water stored (i.e. 'the readily available soil water') will be taken up by the roots to meet the crop's transpiration needs. Hence, when estimating the effective precipitation, we not only have to know the amount of actually depletable water, but also the fraction of the precipitation that becomes deep percolation and soil evaporation.

Effective precipitation as used in CRIWAR is that part of the total precipitation that replaces, or potentially reduces, a corresponding net quantity of required irrigation water. We use the definition of effective precipitation that corresponds with the ICID terminology on the 'field application ratio' and the related efficiencies at crop production level (Bos 1980; Bos and Nugteren 1974; ICID 1978).

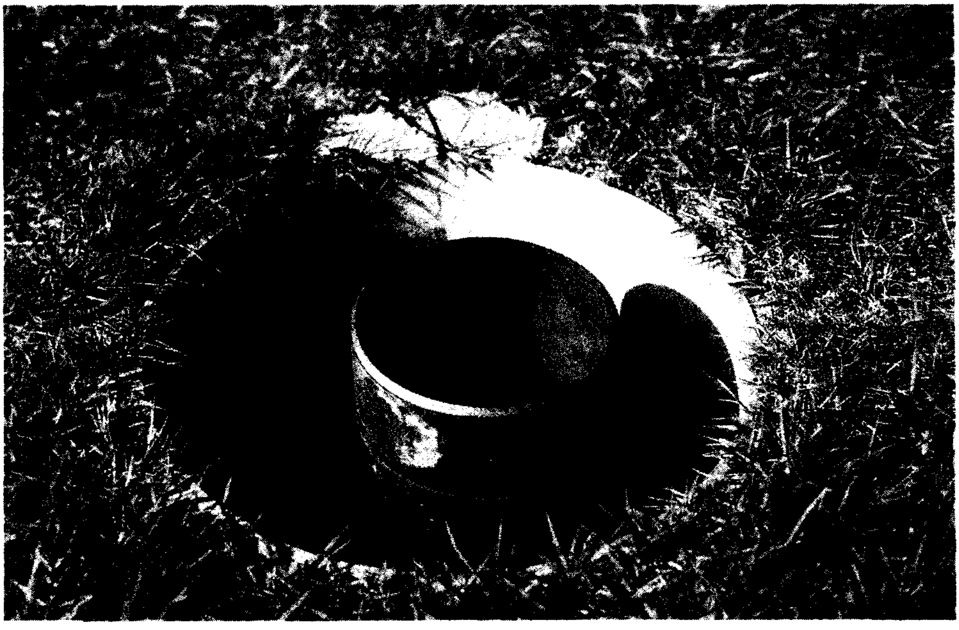

Figure 6.1 The equipment used to measure precipitation influences the quantity measured. The catch diameter, elevation, and surrounding ground cover all influence accuracy

> *'Effective precipitation is that part of the total precipitation on the cropped area, during a specific time period, which is available to meet potential evapotranspiration in the cropped area.'*

This definition limits itself to the 'cropped area'. Precipitation on fallow fields can range from very harmful to a future crop, to highly beneficial to it. Its value depends on a wide range of local conditions, which often discourages research on the effectiveness of precipitation.

The phrase 'during a specific time period' may mean the entire period or any sub-period between sowing or planting and harvesting, or the period between harvests, which is decided upon from an agricultural or operational viewpoint. The above definition limits the effective precipitation to that part 'which is available to meet evapotranspiration in the cropped area'. Precipitation which, upon infiltration, passes through the crop's rootzone may leach harmful salts from the soil. These salts may be leached by the rains during either a fallow period or the crop season, or by non-consumed irrigation water. Water required for leaching serves a significant purpose, but is not included in the definition of effective precipitation. ICID proposed this definition so that data on effective precipitation, and the related field application ratio for different irrigated areas, could be compared without the errors due to the local interpretation of the variable concept of 'leaching water requirement'.

6.2 Major Factors Affecting Effective Precipitation

Various attempts have been made to establish a relationship between total precipitation and effective precipitation, either from individual storms or on a seasonal basis. Some methods use data on (cumulative) precipitation and evapotranspiration, soil data, and crop parameters to estimate the portion of the total precipitation that can be effective. The most sophisticated approaches are based on a dynamic simulation of a complete soil water balance on a day-to-day basis (Feddes et al. 1988; Kabat, v.d. Broek and Feddes 1992). Although these physically based dynamic models can provide very reliable information about the upper limit of the effective precipitation, they also need highly skilled users. Their application is therefore usually confined to sites where an extensive set of input data can be collected. We assume, however, that the user of CRIWAR does not have such detailed measured data.

Unfortunately, a universal formula relating the 'effective' to the total precipitation is not feasible because the ratio is affected by many independent factors, which will be discussed below.

To appreciate the difference between the actual effective precipitation and the CRIWAR-quantified effective precipitation, one needs to have some basic knowledge of the major factors influencing this effectiveness. These factors are grouped in the flow chart in Figure 6.2 (Kopec et al. 1984), which shows the path of measurable precipitation on an irrigated field. To follow this path, we have to make a number of decisions, which are shown as yes/no-exit blocks.

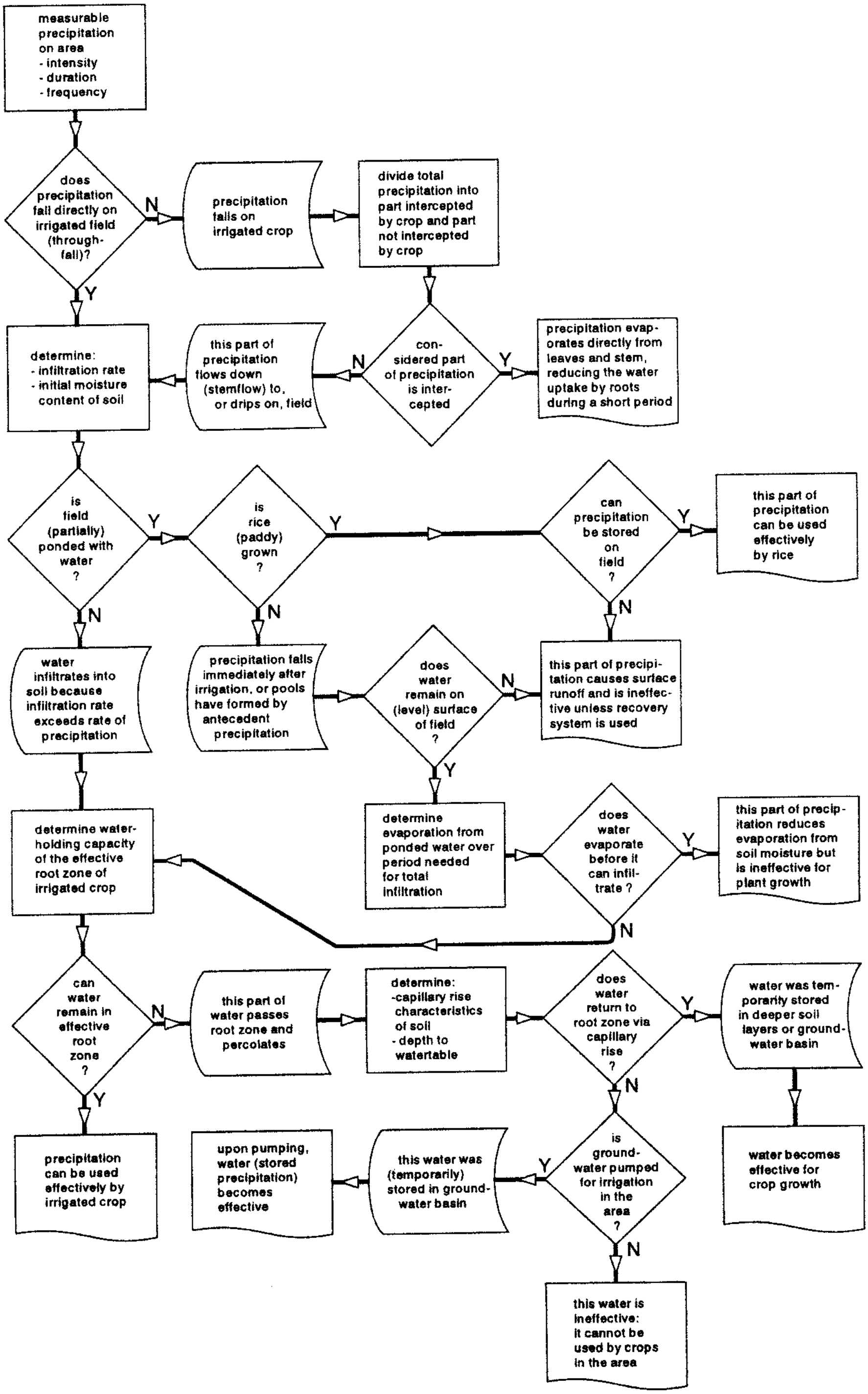

Figure 6.2 Precipitation flow chart (Kopec et al. 1984)

6.2.1 Amount and Frequency of Precipitation

To calculate irrigation water requirements, we have to interpret the precipitation data. Mean precipitation data are usually adequate for us to determine whether both the crop and the leaching requirements are being met in the long term (e.g. by precipitation during the non-irrigation season). To calculate the irrigation water requirement for, say, a 10-day period, however, we have to assess the amount of rainfall that can be reliably expected during that period. In this context, 'reliable' precipitation is usually taken to equal precipitation with a probability of between 80 and 90% (i.e. the amount of precipitation that will, on the average, be equalled or exceeded 80 or 90% of the time in this period).

6.2.2 Time of Occurrence of Precipitation

Snow or rainfall on frozen ground in the non-growing season usually runs off the land on which it falls and provides little or no soil moisture for later evapotranspiration. In contrast, snow on unfrozen ground may yield much of the soil moisture needed immediately after winter for a crop like spring wheat.

If rain occurs immediately after an adequate application of irrigation water, all of it will theoretically be surplus to requirements and will thus be ineffective. At other times, between scheduled applications of irrigation water, the effectiveness of rainfall will be governed by the infiltration rate and the degree to which the soil moisture has been depleted below 'field capacity'.

6.2.3 Rainfall Intensity

Because of runoff, an intensive downpour of, say, 100 mm in one hour may yield much less effective precipitation than the same 100 mm spread over a longer period. Similarly, total precipitation of 100 mm spread over a series of very minor showers may evaporate from the sun-warmed surface without reaching the rootzone. In this case, precipitation is effective only to the extent that it:

- Replaces stored groundwater, which would otherwise have risen to the surface and evaporated;
- Temporarily reduces uptake of water through the roots.

The surplus, being evaporated, does not reduce the irrigation water requirement and is therefore not effective.

6.2.4 Dry and Wet Spell Analysis

In regions where rainfall is erratic, or where short dry periods can be expected in the wet season, we need to know the probability of occurrence of a dry period of 20 or 30 days. If such a dry period coincides with a sensitive stage in crop growth, yields will be reduced (Oldeman and Frere 1982). To avoid this yield reduction, supplemental irrigation water is often applied despite the fact that (erratic) rainfall may fall on the irrigated land.

6.2.5 Irrigated Crops

Shallow-rooting crops (e.g. onions and lettuce) require light but frequent applications of water. In contrast, a heavy downpour will be much more effective for deep-rooted crops (e.g. sugarcane and alfalfa). The amount of evapotranspiration by a plant, and hence the requirement for irrigation water, also varies through the growing cycle. At some stages (e.g. in the early weeks or at the time of final ripening), only small amounts of soil moisture are removed per unit of time. With some crops, we may want to restrict evapotranspiration by reducing or stopping irrigation (e.g. to increase the sugar content of cane just before it is cut). Rainfall in sizeable quantities at these stages of plant growth will often be more than required and will therefore be less effective unless carried over as soil moisture for the next crop.

In general, it can be said that precipitation in excess of the storage capacity in the rootzone is ineffective. The USDA Soil Conservation Service (1970) developed a method to estimate the effective precipitation in which this rule is used. This method will be explained in Section 6.3.

6.2.6 Infiltration Rate

The infiltration rate is a characteristic of the soil and its state of preparation (e.g. whether it is tilled or not). Under otherwise identical conditions, a given shower of rain may be very effective if the soil has a sandy surface texture or has just been tilled. Conversely, it may be highly ineffective if the soil is an impermeable clay or has formed an impermeable caked surface; most of the rainfall will then either run off or be lost by evaporation from the surface. If lost by evaporation, it is ineffective to the extent that surface evaporation of standing water exceeds losses of moisture that would have risen by capillary action (and evaporated) in the absence of rain.

6.2.7 Water-Holding Capacity

The degree to which a soil is capable of holding or retaining moisture between field capacity and wilting point will limit the proportion of rainfall that will be held for subsequent use by the crop. A very coarse-textured sandy soil may allow rapid drainage through and beyond the rootzone to the underlying strata. A clay soil may be capable of retaining more moisture, provided that the rate of precipitation is sufficiently low to allow time for it to infiltrate into the rootzone.

6.2.8 Soil Water Movement

Much research has been done on the physics of soil water movement, and complex models have been developed to estimate the relationship between the soil ↔ plant ↔ atmosphere ↔ water. The most sophisticated approaches are based on a dynamic simulation of a complete soil water balance on a day-to-day basis (Feddes e.a. 1988; Kabat e.a. 1992).

6.2.9 Field Slope

The general slope of the ground surface is an important factor in determining the rate of application of irrigation water, particularly in furrow and border irrigation. Likewise, in intense storms or rapid snow melt, the slope of the ground will affect the degree of runoff and hence the proportion of water that will be retained in the soil. Precipitation on level basins with dry-foot crops may infiltrate entirely. In rice basins, part or all of the rainfall may be stored on the field.

6.2.10 Land Surface Condition

A dense crop cover will intercept precipitation and reduce the rate of runoff. This allows more time for the precipitation to infiltrate and thus increases the effective part of precipitation. The presence of surface mulches will also impede runoff and produce the same effect.

Tilling is an important factor. A hard, compacted surface reduces the rate of infiltration and increases runoff. Conversely, a well-tilled field will impede the surface flow of water and will increase both the infiltration rate and its duration. This can significantly increase the effectiveness of precipitation. Most soil conservation measures aiming at a reduction of runoff and an increase in the retention time of surface water have a similar effect.

6.2.11 Depth to Groundwater

The depth to groundwater has a major influence on the extent to which capillarity will bring groundwater into the rootzone or to the soil surface. If the plant roots extend into the capillary zone, much of the rain water that had previously percolated to the shallow groundwater remains in storage for subsequent evapotranspiration, thus increasing the effectiveness of previous precipitation. Capillary rise will be greater in fine-textured soils than in coarse-textured soils.

6.2.12 Irrigation Water Supply Method

From the viewpoint of an irrigation system operator, there are various methods of supplying water to a group inlet of several small farms or to an individual inlet of one large farm:
- Continuous supply;
- Rotational supply;
- Supply on demand in advance;
- Supply on instantaneous demand.

With the first two methods, only the statistically dependable part of the rainfall can be counted on to save irrigation water. Thus, although the other part of the rainfall may be highly effective in terms of the definition adopted, with these two water supply methods, it does not permit a saving of irrigation water. With the third method, a saving of irrigation water in the event of effective rainfall is possible only if the unused irrigation water can remain in storage, or can be stored within the irrigation system for later use. The fourth water supply method allows the farmer to save irrigation water in the event of effective rainfall.

6.3 The USDA Method

In CRIWAR, the goal is to develop a generally applicable simulation program that is able to calculate the irrigation water requirements. CRIWAR uses only basic meteorological, soil, and crop data that are commonly available to most of its potential users. To calculate the effective precipitation, CRIWAR uses a semi-empirical method developed by the U.S. Department of Agriculture (1970). This method is combined with an improved estimate of the effect of the net irrigation application depth on effective precipitation. On the basis of the information given in Section 6.2, the user is free either to reduce or to increase the CRIWAR estimate of the effective precipitation.

6.3.1 The Three Major Factors Used

The USDA method is based on a soil water balance performed for 22 meteorological stations in the U.S.A., with the use of 50 years of data. It considers deep percolation to the groundwater basin and soil-profile depletion by evapotranspiration. Surface runoff is accounted for only marginally in this method. Three factors are considered to influence the effectiveness of precipitation. They will be discussed below.

Mean Cumulative Monthly Precipitation
Rain storms of large magnitude and high intensity will supply water in excess of that which can be stored in the soil profile. Deep percolation to the groundwater and surface runoff will usually be high. In areas with light total precipitation during the growing season, these losses will not occur as frequently. Consequently, by comparison, the effectiveness of precipitation in areas with light precipitation will be relatively high.

Mean Cumulative Monthly Evapotranspiration
When the evapotranspiration rate is high, the soil water will be rapidly depleted. As a consequence, a large amount of water can be stored in the soil profile again before it reaches field capacity. When the evapotranspiration rate is low, the storage capacity for precipitation will be provided at a slower rate. Thus, the higher the evapotranspiration rate, the higher the effectiveness of precipitation.

Irrigation Application Depth

For most irrigation areas, the depth of water application per irrigation turn is assumed to equal the readily available soil water that can be stored in the rootzone. The capacity of the soil profile to store water for crop use depends on the soil type and the effective rooting depth. A high storage capacity within the rootzone indicates a relatively high effectiveness of precipitation.

6.3.2 Calculation Method

Figure 6.3 shows the relationship between the above three factors. It shows that the average monthly effective precipitation can exceed neither the total average monthly rainfall nor the total evapotranspiration. For the same evapotranspiration rate, the effectiveness of precipitation, expressed as a percentage of the total precipitation, decreases with the higher total precipitation. The relationship in Figure 6.3 is valid for a net irrigation water application depth of 75 mm per turn.

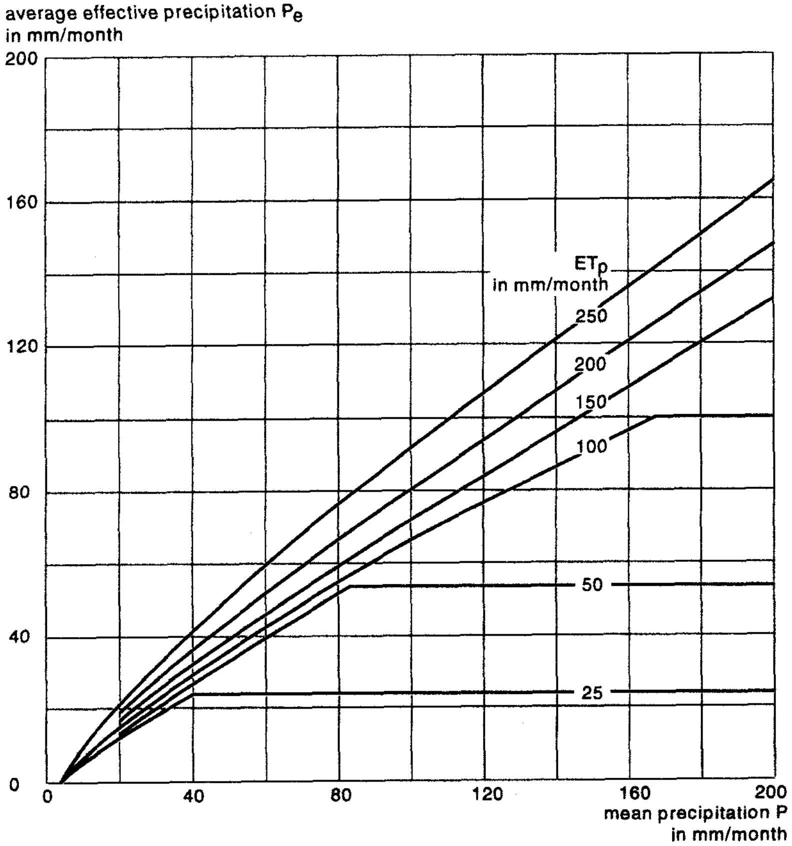

Figure 6.3 Average monthly effective precipitation as related to the mean total monthly precipitation and the average monthly evapotranspiration for a net irrigation application depth of 75 mm per turn

In CRIWAR, the effective precipitation is calculated on a monthly basis by an empirical expression which accurately describes the relationship in Figure 6.3

$$P_e = f(1.253P^{0.824} - 2.935) \times 10^{0.001\mathrm{ET_p}} \tag{6.1}$$

where

P_e = effective precipitation per month [mm/month]
P = total precipitation per month [mm/month]
ET_p = total crop evapotranspiration per month [mm/month]
f = a correction factor which depends on the dept of the irrigation water application per turn [–]

The factor f equals 1.0 if the irrigation water application depth is 75 mm per turn. For other application depths, the value of f equals

$$f = 0.133 + 0.201 \ln D_a \qquad \textit{if } D_a < 75 \text{ mm/turn} \tag{6.2}$$

and

$$f = 0.946 + 7.3 \times 10^{-4} \times D_a \qquad \textit{if } D_a \geq 75 \text{ mm/turn} \tag{6.3}$$

If the use of these equations results in an effective precipitation that exceeds either ET_p or P, CRIWAR reduces the P_e value to the lowest of these two. When the mean total rainfall per month is less than 12.5 mm, CRIWAR assumes all precipitation to be 100% effective.

If the calculation per 10-days is requested, CRIWAR converts the user-given precipitation data per 10-days into total monthly data. Also the calculated ET_p, expressed in mm/10-days, is converted to total monthly crop evapotranspiration. With these converted data, the effective rainfall is estimated from Equations 6.1, 6.2, and 6.3. After that, the calculated effective precipitation in mm/month is converted back into mm/10-days.

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7 Capillary Rise

7.1 Introduction

Figure 7.1 shows the water balance of an irrigated field. As illustrated, the crop receives water through precipitation, P, (see Chapter 6 for the related effective precipitation, P_e), through irrigation, and through capillary rise. If the depth to the watertable is shallow (less than 3 m) and the soil is fine-textured, capillary rise can contribute a significant volume of water to the rootzone of the crop. For the watertable to remain stable, however, groundwater must flow laterally into the irrigated area; otherwise the capillary rise will decrease with the falling watertable. Because groundwater flow is not simulated in CRIWAR, the capillary component is not corrected for in the irrigation water requirements. This chapter illustrates when capillary rise is a potential source of water. If that is so, the CRIWAR-calculated crop water requirements should be corrected for the contribution from groundwater.

7.2 The Driving Force of Capillary Water

Soil can be regarded as a mixture of solids and pores, with the pores forming capillary tubes. If the bottom end of a capillary tube is inserted in water, the water will rise into the tube under the influence of capillary forces (Figure 7.2). The total

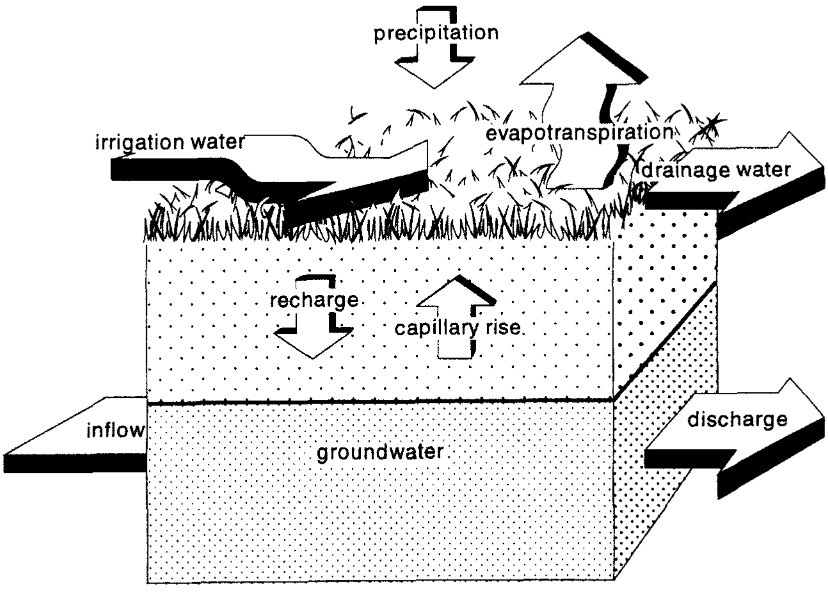

Figure 7.1 Schematic water balance in an irrigated field (Bos 1984)

upward force, $F\uparrow$, lifting the water column, is obtained by multiplying the vertical component of surface tension by the circumference of the capillary tube

$$F\uparrow = \sigma \cos\alpha \times 2\pi r \tag{7.1}$$

where

$F\uparrow$ = upward force (N)
σ = surface tension of water against air ($\sigma = 0.073$ kg.s^{-2} at 20 °C)
α = contact angle of water with the tube (rad); ($\cos\alpha \simeq 1$)
r = equivalent radius of the tube (m)

Because of gravity, the water column of height C and mass $\pi r^2 C\rho$ exerts a downward force, $F\downarrow$, that opposes the capillary rise

$$F\downarrow = \pi r^2 C\rho \times g \tag{7.2}$$

where

$F\downarrow$ = downward force (N)
ρ = density of water ($\rho = 1000$ kg/m^3)
g = acceleration due to gravity ($g = 9.81$ m/s^2)
C = height of capillary rise (m)

At equilibrium, the upward force, $F\uparrow$, must equal the downward force, $F\downarrow$. Hence

$$\sigma \cos\alpha \times 2\pi r = \pi r^2 C\rho \times g$$

or

$$C = \frac{2\sigma \cos\alpha}{\rho g r} \tag{7.3}$$

Substituting the values for σ, $\cos\alpha$, ρ, and g as given above into Equation 7.3 gives an expression for the height of the capillary rise

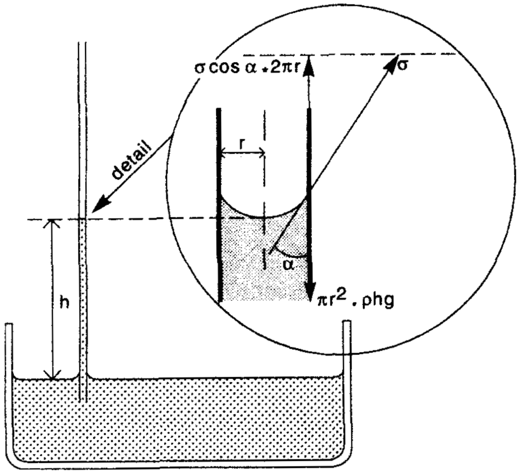

Figure 7.2 Capillary rise of water (Kabat and Beekma 1994)

$$C = \frac{0.15}{r} \qquad (7.4)$$

Thus, the smaller the radius of the tube, the higher the capillary rise. Real soils, however, do not consist of capillaries of one uniform diameter. Further, water movement in a real soil is influenced by thermal, electrical, and solute-concentration gradients. For our purposes, however, let us assume that an elementary water particle has three types of interchangeable energy per unit of volume:

$\rho v^2/2$ = kinetic energy per unit of volume (Pa)
ρgz = potential energy per unit of volume (Pa)
p = pressure energy per unit of volume (Pa)

The flow velocity of water in the soil pore is very low, so $\rho v^2/2$ is negligible. If the other two energies of water are divided by ρg, the hydraulic energy head, h_{hydr}, can be written as

$$h_{hydr} = \frac{p}{\rho g} + z \qquad (7.5)$$

The soil water pressure head, $h = p/\rho g$, is negative in unsaturated soil because energy is needed to withdraw water against the soil-matric forces. At the groundwater level, atmospheric pressure exists and therefore $h = p/\rho g = 0$.

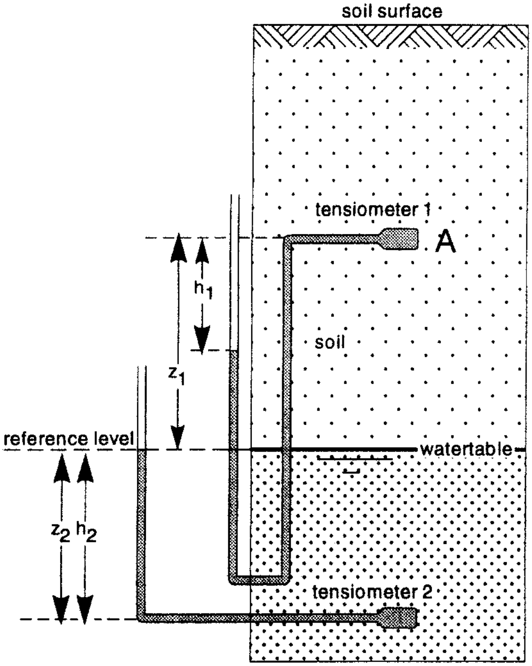

Figure 7.3 The pressure head, h, at point A, located at a height, z, above a reference level

The elevation head, z, is determined at each point by the elevation of that point relative to a certain reference level, with z being positive above the reference level and negative below it (Figure 7.3).

7.3 Steady-State Capillary Rise

The most simple case of capillary flow is that of steady-state vertical flow in an isotropic media (i.e. a soil whose hydraulic conductivity is the same in every direction). The flow equation is obtained by rewriting Darcy's Equation

$$q = -k\left(\frac{dh}{dz} + 1\right) \tag{7.6}$$

where

q = vertical flow rate per unit area (m/d)
k = hydraulic conductivity as a function of h (m/d)
h = soil water pressure head (m)
z = elevation head, being positive in the upward direction (m)

Rearranging Equation 7.6 yields

$$\frac{dz}{dh} = \frac{-1}{1 + \frac{q}{k}} \tag{7.7}$$

To calculate the pressure head distribution (i.e. the relationship between z and h for a certain k-relationship and a specified flow rate q), Equation 7.7 should be integrated. This yields

$$\int_0^C dz = -\int_0^{h_{pr}} \frac{dh}{1 + \frac{q}{k}} \tag{7.8}$$

where

h_{pr} = pressure head, at the upper boundary condition (m)
C = height of capillary rise for flow rate q (m)

If the pressure head (and thus also h_{pr}) and the hydraulic conductivity are measured in the soil profile as a function of elevation (head), Equation 7.8 can be solved by integration between the pressure head at the groundwater level (h = 0 m) and the measured value of h_{pr} for constant values of q. For complex combinations of these parameters, Equation 7.8 (one for each soil layer) can be solved by numerical models (Wesseling 1991).

As mentioned earlier, the capillary flow rate and the height of capillary rise above the watertable both depend on the soil type and on the pressure head differential between the watertable and the upper boundary condition. If, for example, the lower side of the effective rooting depth is the upper boundary, and if we assume a stable watertable and a gradual increase in the soil water pressure head from zero at the groundwater level to a value of $h_{pr} = -160$ m ($pF = 4.2$) at the upper boundary (a value corresponding with a soil water content at wilting point), we can calculate the relationship between C and q. Figure 7.4 shows this relationship for four undisturbed Dutch soils (Wōsten et al. 1994).

Figure 7.4. illustrates several interesting points:

- Upward flow rates of more than 2 mm/day are common for the above boundary conditions. Nevertheless, the height over which this flow can rise depends on the soil type (and structure), but even for coarse sand, this height is still about 0.4 m;
- The 'maximum' height of capillary rise in heavy clay is much greater than that in coarse sand. However, because of the low hydraulic conductivity of clay, the flow rate is low;
- If the lower side of the effective rooting depth is near the watertable (say < 0.5 m), the groundwater contribution to crop water consumption is considerable;

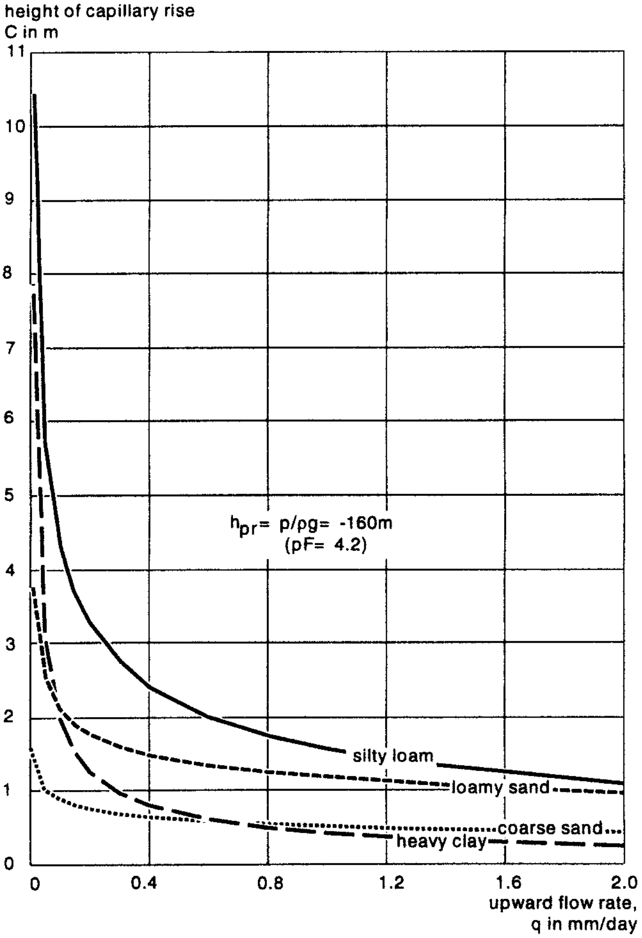

Figure 7.4 Height of capillary rise as a function of the upward flow rate for four undisturbed Dutch soils

- In fine-textured soils, the capillary flow rate varies more with the height than in coarse-textured soils.

If the watertable remains at a constant level as a result of the lateral inflow of groundwater, the capillary flow rate will remain constant. If the groundwater is not fed by lateral inflow, however, capillary flow will cause the watertable to fall. As shown in Figure 7.4, with a greater depth to the watertable, the capillary flow decreases sharply. The end result is that the watertable falls to a depth where the capillary flow rate is zero.

As mentioned earlier, Figure 7.4 is based on the assumption that the soil water pressure at the lower side of the effective rootzone is $h_{pr} = -160$ m (wilting point). Following an irrigation water application, soil water content will increase and the capillary flow rate will decrease with the increase in h_{pr}. As a result of variable soil water content, the depth to the watertable, and the effective rooting depth, the capillary contribution to crop water consumption varies with time. But, as has already been stated, this contribution is not modelled in CRIWAR.

7.4 Rooting Depth

If the water that rises above the watertable through capillary action reaches the effective rootzone of the irrigated crop, the crop may consume this water. Hence, to estimate the capillary contribution of water, we need information on:

- The depth to the watertable. This can be measured in an observation tube;
- The soil physical (capillary) characteristics of the soil(s) in the irrigated area. Figure 7.4 shows some examples;
- The effective rooting depth of the irrigated crop. The rooting depth of a crop, however, varies with the type, variety, and age of the crop, with the soil type and texture, with the depth to the watertable, with the irrigation frequency, and so on. Because the actual rooting depth of irrigated crops is difficult to measure, only rough information will be available on this subject. Table 7.1 can be used for a preliminary estimate of the effective rooting depth of fully grown crops.

Table 7.1 Approximate effective rooting depths (m) of fully grown crops

Crop	Rooting depth (m)	Crop	Rooting depth (m)
Field crops		**Vegetables**	
Barley	0.90-1.05	Artichoke	0.60-0.9
Wheat	0.75-1.05	Asparagus	1.80
Cotton	0.60-1.8	Bean	0.45-0.60
Lucerne	1.20-1.8	Beetroot	0.30-0.45
Maize	0.60-0.9	Beet (sugar)	0.45-0.75
Oats	0.60-0.75	Broccoli	0.60
Sorghum	0.60-0.9	Brussel sprout	0.60
Sugar cane	0.45-1.05	Cabbage	0.60
Tobacco	0.60-1.2	Carrot	0.45-0.60
		Cauliflower	0.60
Horticultural crops		Celery	0.60
		Cucumber	0.45-0.60
Apple	0.75-1.2	Lettuce	0.15-0.45
Apricot	0.60-1.4	Onion	0.30
Banana	0.30-0.60	Parsnip	0.60-0.90
Cherry	0.75-1.20	Potato	0.60-0.90
Citrus	0.60-1.20	Sweet potato	0.60-0.90
Grape	0.45-0.90	Pea	0.45-0.60
Passion fruit	0.30-0.45	Pumpkin	0.90-1.20
Peach	0.60-1.20	Radish	0.30
Pear	0.60-1.20	Rock melon	0.60
Plum	0.75-1.20	Spinach	0.60-0.90
Strawberry	0.30-0.45	Swede	0.60-0.90
		Tomato	0.60-1.2
Pasture and Fodder Crops		Turnip	0.30-0.60
		Water melon	0.60-0.90
Lucerne	1.20-1.80		
Millet(fodder)	0.30-0.60		
Pastures	0.30-0.75		
Sorghum alum	0.90-1.20		
Sudan grass	0.90-1.20		

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8 Irrigation Water Requirements

8.1 The Concept

The relative magnitude of volumes of water flowing through an 'average' irrigation system is illustrated in Figure 8.1. As can be seen, more water is delivered from the water source than is consumed (i.e. evapotranspired) by the irrigated crops. Most of the non-consumed part of the delivered irrigation water returns to the groundwater basin and to the downstream surface water system. Provided that the quality of this return flow is acceptable, it can be re-used downstream. In many river basins, water is used and re-used by a variety of agricultural, environmental, urban, industrial, and recreational users. During this use and re-use, up to 90% of all water in the basin may be consumed.

To calculate the volume, V_i, of irrigation water required to be delivered through the flow control structure serving the *i*th command area, we multiply the crop irrigation water requirements, ET_p - P_e, as calculated by CRIWAR, by the relevant irrigation water-use ratios. These ratios quantify components of the water balance in a spatial context over a specific time period. Depending on the command area under consideration, the relevant ratios are combinations of the field-application ratio, R_a, the distribution ratio, R_d, and the conveyance ratio, R_c. (See Sections 8.2, 8.3, and 8.4 for definitions.)

8.2 Water-Balance Ratios

8.2.1 Field-Application Ratio

The irrigation water requirement at the field inlet depends on the value of ET_p - P_e of the irrigated crop and on the field-application ratio, R_a. The ICID standard definition for the field-application ratio (efficiency) is

$$R_a = \frac{V_m}{V_f} \tag{8.1}$$

where

V_m = volume of irrigation water needed, and made available, to avoid undesirable stress in the crops throughout the growing cycle (m^3/period)

V_f = volume of irrigation water delivered to the fields during the period under consideration (m^3/period)

The value of V_m is difficult to establish on a real-time basis because many complicated field measurements would be needed. The method that is used to quantify V_m, however, is not so very important, provided that the same (realistic) method is used for all command areas (lateral or tertiary units) within the irrigated area. For practical purposes, we can assume that V_m equals the evapotranspiration by the irrigated crop, minus the effective part of the precipitation (i.e. the $ET_p - P_e$ as calculated by CRIWAR). The water requirement at the field inlet then equals

$$V_f = \frac{ET_p - P_e}{R_{a,target}} \tag{8.2}$$

The target value of the field-application ratio, $R_{a,target}$, depends on the level of

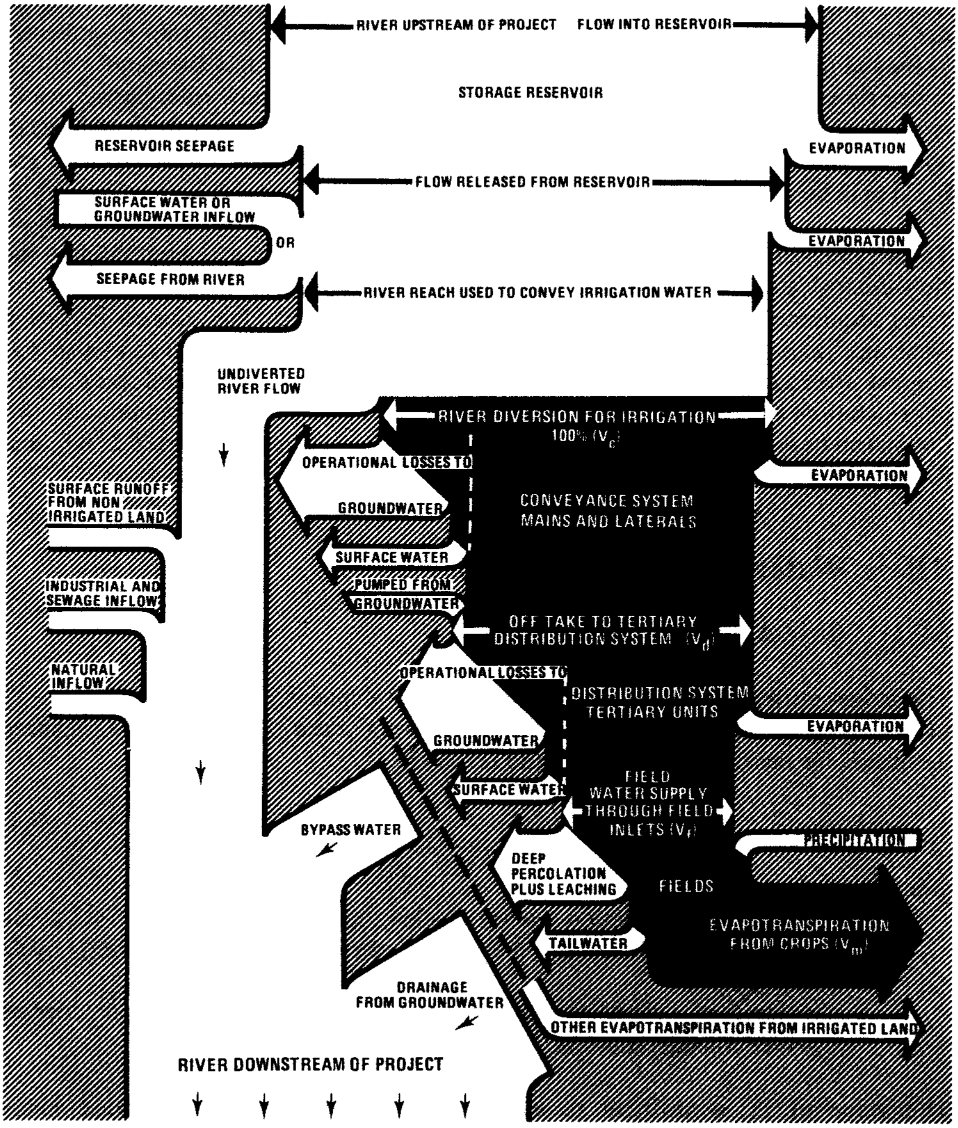


Figure 8.1 The relative volumes of water flowing through an 'average' irrigation system (Bos 1979)

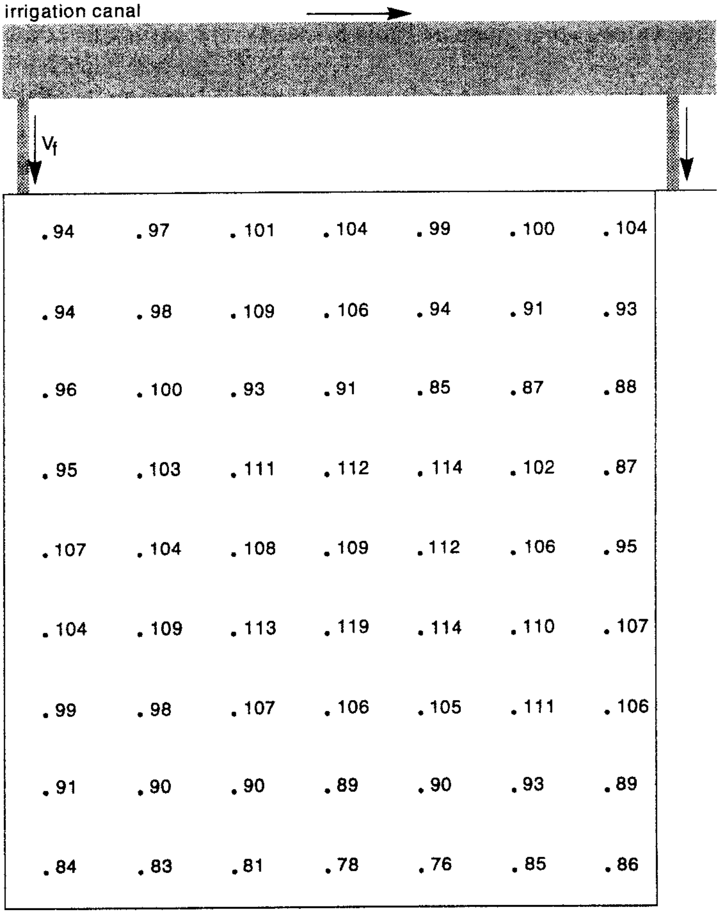
technology used to apply water, on the climate, and on the crop practice (dry-foot crop or ponded rice). How they can be determined is shown below.

Dry-Foot Crops

The ability to apply irrigation water uniformly to a field is an important criterion in determining the level of technology to be used. At the same time, this uniformity influences the volume of water (per irrigation turn) that needs to be applied to the field, in addition to the crop irrigation water requirements. As an example, let us consider a level basin to which $V_m = 100$ mm for the considered turn. If the applied water depths, $V_{a,i}$, (volume or depth per irrigation turn) to parts of an irrigated field are measured, we can assume

$$V_f = \sum V_{a,i} \tag{8.3}$$

If, in Equation 8.1, the volume V_m equals V_f, the field application ratio is 1.0 (100%). Nevertheless, 50% of the field has then been given more water than V_m; the



.94	.97	.101	.104	.99	.100	.104
.94	.98	.109	.106	.94	.91	.93
.96	.100	.93	.91	.85	.87	.88
.95	.103	.111	.112	.114	.102	.87
.107	.104	.108	.109	.112	.106	.95
.104	.109	.113	.119	.114	.110	.107
.99	.98	.107	.106	.105	.111	.106
.91	.90	.90	.89	.90	.93	.89
.84	.83	.81	.78	.76	.85	.86

Figure 8.2 Measured depths ($V_{a,i}$ in mm) of irrigation water applied to a level basin

other 50% has received less. In the part of the field that has received less, salt will accumulate in the rootzone during the irrigation season. This would not cause a problem if sufficient off-season precipitation is available to leach these salts. Hence, the fraction, F, of the field that is allowed to receive less water than V_m ($= ET_p - P_e$) depends on the climate.

Till and Bos (1985) assumed a normal distribution of $V_{a,i}$ and recommended that the summed target flow to a field (or volume of flow over a considered period) equals

$$V_{f,target} = (\sum V_{a,i})_{target} = (1 + s\ T_p) \times \sum V_{m,intended} \tag{8.4}$$

where the standard deviation, s, of the water-application ratio, $V_{a,i}/V_f$, should be measured for an applied volume (or depth) of water that approximates $V_{m,intended}$. The latter because the uniformity of water application depends on the depth of water applied. For the example of Figure 8.2, the value of s equals 0.11.

T_p is a statistical value that is exceeded by a random variable, normally distributed, with zero mean, and with standard deviation units. Values of T_p versus F are listed in statistical handbooks. An extract is given in Table 8.1.

As shown above, the target value of V_f depends on the standard deviation, s, of the 'irrigation water application' and on the fraction of the field where a water shortage is acceptable (F in %). The standard deviation depends on the level of technology available to apply water uniformly, and on the 'quality of management and operation by the farmer'. As mentioned earlier, the percentage of the area where a water shortage is acceptable depends on the climate. Till and Bos (1985) recommend a T_p-value of 0.67 if off-season precipitation is available to leach the accumulated salts. In arid and semi-arid climates, this may not be the case. Then a value of $T_p = 2.0$ (F is about 2.5%) is recommended. The target value of the field-application ratio for dry-foot (non-rice) crops is then

$$R_{a,target} = \frac{V_m}{(1 + s\ T_p) \times V_m} \tag{8.5}$$

If the field of Figure 8.2 is in a climate with sufficient rain to leach the accumulated salts ($F = 25\%$), Equation 8.5 gives

$$R_{a,target,rain} = \frac{100}{(1 + 0.11 \times 0.67) \times 100} = 0.93$$

Table 8.1 Values of T_p versus F

F (in %)	T_p (dimensionless)
50	0
25	0.67
10	1.28
5	1.64
2.5	1.96
1.0	2.33

In arid climates, the fraction F should be as low as 2.5%. Hence

$$R_{a,target,arid} = \frac{100}{(1 + 0.11 \times 2.00) \times 100} = 0.82$$

Substitution of the latter target values into Equation 8.2 shows that, under arid conditions, the required volume of irrigation water, V_f, is 0.93/0.82 = 1.13 times greater than under more humid conditions. Since water is a scarcer resource, however, arid conditions would require a higher level of technology and related management (smaller value of s).

Paddy Rice

For paddy rice, the ICID (Senga and Mistry 1989) recommended that the seepage from the field, $V_{f,seepage}$, be added to the target volume of water application. Hence

$$R_{a,target,paddy} = \frac{V_m}{(1 + s\,T_p) \times V_m + V_{f,seepage}} \tag{8.6}$$

For well-levelled fields with ponded water, the values of both s and T_p approach zero. Equation 8.6 shows that the target ratio for paddy rice decreases with increasing seepage from the field. A lower limit should be set to the target field-application ratio; if there is too much seepage, paddy should not be grown.

8.3 Distribution Ratio

The simplest, and yet probably the most important, hydraulic performance indicator is (Clemmens and Bos 1990; Bos et al. 1991; Wolters 1992)

$$\text{Water Delivery Performance} = \frac{\text{Actually Delivered Volume of Water}}{\text{Intended Volume of Delivered Water}} \tag{8.7}$$

Over a sufficiently long time frame (e.g. a month, or over three or four rotational time periods), it can be assumed that if the Water Delivery Performance (*WDP*) is close to unity, then the water management inputs must be effective. The related water balance ratio can then be high without causing water shortage to some of the farmers. The effectiveness (uniformity) of water delivery can be quantified by the standard deviation of the *WDP* within the tertiary (irrigation) unit under consideration; hence, by the standard deviation of the measured $V_{f,actual}/V_{f,intended}$ values within the unit.

A target for the flow that should be delivered to a group of water users in one irrigation unit depends on:

- The value of the above standard deviation, s;
- The interpretation of the concept 'intended water delivery to most users'.

In other words, which part (F in %) of the fields/users may receive less water than they need to meet all water requirements. It further depends on:

- The seepage from the tertiary water distribution system, $V_{d,seepage}$.

Table 8.2 Example of actual water delivery along the Los Sauces Canal for the turn starting on 17 Dec. *1994*

Name of farmer	Area with crops (ha)	Actually delivered m³/turn	Actually delivered mm/ha	Intended delivery m³/turn	Intended delivery mm/ha	Water delivery performance
Canal filling		(4838)				
Olivares	4.00	3030	76	2640	66	1.15
Gonzales	4.08	3047	75	2652	65	1.15
Rinaldi	10.06	7188	71	6338	63	1.13
Vespa	2.68	1768	67	1581	59	1.13
Garrido	1.09	2396	220	2104	193	1.14
Blanco	12.61	7808	61	7314	58	1.05
Bagorda	9.32	2297	25	5033	54	0.46
Martinez	3.95	3286	83	3160	80	1.04
Mondello	3.26	2123	65	2119	65	1.00
Delgado	0.96	1034	108	1018	106	1.02
Cardenas	1.68	6064	52	8526	73	0.71
Martinez	5.04	3453	69	3730	74	0.93
Disentimio	5.55	2880	52	3219	58	0.89
Saez	7.26	2759	38	3194	44	0.86
Valent	3.77	906	24	1056	28	0.86
Corti	8.00	6364	80	7440	93	0.86
Terreni	11.48	7014	61	7921	69	0.89
Escudero	2.25	2909	129	3195	142	0.91
Totals:	107.04	66325+(4838)		72240		
		Average:	75.2		77.2	0.95
		Standard deviation:	43.0		36.9	0.17

The summed target flow (or volume of flow over a considered period) serving a group of field off-takes equals

$$V_{d,target} = (1 + s\,T_p) \times \sum V_{f,i,intended} + V_{d,seepage} \tag{8.8}$$

The standard deviation, s, and the intended flow to be delivered to the i-th off-take, $V_{d,i,intended}$, were defined above. Values of T_p versus F are listed in Table 8.1.

As an example, let us consider the measured water delivery to 19 farms in the Los Sauces Unit, Tunuyan System, Argentina (Figure 8.3). The intended water deliveries as shown in Table 8.2 are the average values of V_f for the farms. The actually delivered flows were measured by a long-throated flume equipped with a water-level recorder (Clemmens et al. 1993)

The distribution ratio quantifies the water balance of the tertiary system. For the Los Sauces Canal, this ratio equals

$$R_{d,Sauces} = \frac{\sum V_{f,actual}}{V_d} \tag{8.9}$$

The volumes can be taken from Table 8.2. Canal filling until the most downstream water user received water required 4838 m³ and seepage was 3316 m³. Hence

$$R_{d,Sauces} = \frac{66326}{66326 + 4838 + 3316} = 0.89 \qquad (8.10)$$

For the irrigation turn starting 17 December 1994, the average Water Delivery Performance (*WDP*) was 0.95. Hence, the management input by the gate operator can be termed effective. The effectiveness (uniformity) of water delivery can be quantified by the standard deviation of the *WDP* within the (tertiary) irrigation unit; hence, by the standard deviation of the measured $V_{f,actual}/V_{f,intended}$ values within the unit, which is $s = 0.17$. The timing of the flow into the farm inlets is fairly accurate. Gate opening and closure is always closely attended to by two (or three) persons; the gate operator, the irrigator who is going to receive water, and (commonly) the irrigator who is about to end his turn.

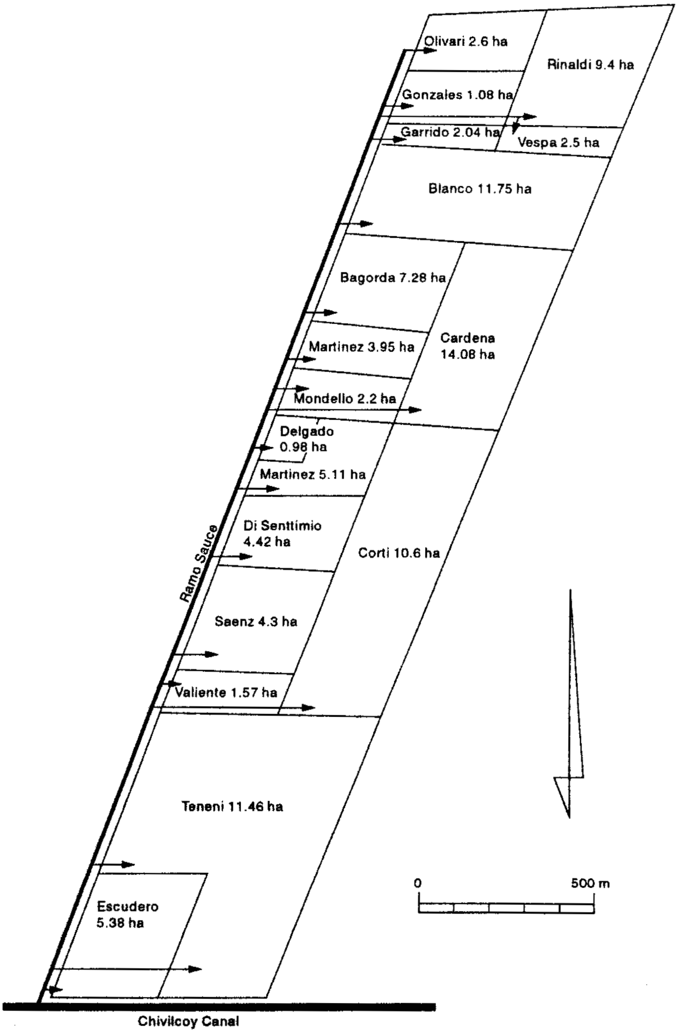


Figure 8.3 Location of farms and related farm inlets along the Los Sauces canal

A target rate for the flow that should be delivered to a group of water users in one irrigation unit depends on:

- The value of the above standard deviation, s, and on
- The interpretation of the concept 'intended water delivery to most users'.

In other words, which percentage (F in %) of the fields (or users) may receive less water than needed to meet all water requirements? It further depends on:

- The seepage losses from the tertiary water distribution system. In the above example $V_{d,seepage} = 4838 + 3316 = 8154$ m^3/turn.

The summed target flow rate (or volume of flow over a considered period) serving a group of field off-takes equals

$$V_{d,target} = (1 + sT_p) \times \sum V_{farm,i,intended} + V_{d,seepage} \tag{8.11}$$

For the above example, the standard deviation, $s = 0.17$, and the total intended flow to be delivered to all farm inlets, $\sum V_{farm,i,intended} = 72\ 240$ m^3/turn, were defined above. Values of T_p versus F are listed in Table 8.1. If we tentatively assume $F = 25\%$, and thus $T_p = 0.67$, we can write

$$V_{d,Sauce,target} = (1 + 0.17 \times 0.67)\ (72240) + 8154 = 88468 \text{ m}^3$$

As shown above, the target flow is strongly influenced by the standard deviation, s, of the water delivery ratio and by the acceptability of water shortage (F in %). In calculating the above target volume, we tentatively assumed $F = 25\%$. Table 8.2, however, shows a *WDP* ratio below 1.0 for 50% of the farms during the irrigation turn. If that would be acceptable (in the long term), T_p would become zero, and

$$V_{d,Sauce,target} = (1 + 0)\ (72240) + 8154 = 80394 \text{ m}^3$$

being slightly more than the value diverted during the 17 December turn.

In deciding on the proper F-value, irrigation managers will likely have to rely on past experience to see what is an acceptable value. The Los Sauces Unit receives water for 25 hours once every 13 days. During the example turn of Table 8.2, the most downstream user received water first; during the next turn, he is last in line. As a result, the *WDP* for each user varies per turn and an F-value of 50% is accepted by the farmers.

8.4 Overall Consumed Ratio

The overall (or project) consumed ratio quantifies the fraction of irrigation water evapotranspired by the crops in the water balance of the irrigated area (Willardson et al. 1994). Assuming negligible non-irrigation water deliveries, we can define it as (Bos and Nugteren 1974)

$$R_p = \frac{ET_p - P_e}{V_c + V_1} \tag{8.12}$$

where

V_c = volume of irrigation water diverted or pumped from the river or reservoir (surface water source)

V_l = inflow from other sources to the conveyance system

As was explained in Chapters 5 and 6, the value of $(ET_p - P_e)$ for the irrigated area is entirely determined by the crop, the climate, and the interval between water applications. Hence, the actual value of the overall consumed ratio varies with the actual value of $(V_c + V_l)$, being the volume of irrigation water delivered to the command area.

Because the inflows V_c and V_l are among the very first values that should be measured (together with the cropped area, the cropping pattern, and climatological data), the overall consumed ratio is the first water balance indicator that should be available for each irrigated area. For water management within an existing irrigated area, we recommend that a target R_p-value be set, and that the actual overall consumed ratio be calculated on both a monthly (or 10-day) and an annual basis. As soon as dependable information is available on the monthly R_p-value, the total irrigation water requirements during the considered period (month) can be calculated with

$$(V_c + V_l)_{target} = \frac{ET_p - P_e}{R_{p,target}} \tag{8.13}$$

In Equation 8.13, as was mentioned above, we assumed that the order of magnitude of the non-irrigation deliveries is negligible.

As in Section 8.3, the target value for the overall consumed ratio depends on the Water Delivery Performance (*WDP*). If the *WDP* is close to unity for all (tertiary) units to which water is delivered, the management inputs must be effective. The related overall consumed ratio can then be high without causing water shortage in parts of the tertiary units. The effectiveness (uniformity) of water delivery can be quantified by the standard deviation of the *WDP* within the irrigated area under consideration; hence by the standard deviation of the measured $V_{d,actual}/V_{d,intended}$ values.

A target for the flow that should be diverted from the water source depends on:
- The value of the above standard deviation, s, and on:
- The interpretation of the concept 'intended water delivery to most tertiary units'.

In other words, which percentage (F in %) of the user groups may receive less water than they need to meet all water requirements? It further depends on:
- The seepage from the conveyance system, $V_{c,seepage}$.

The summed target flow rate (or volume of flow over a considered period) equals

$$(V_c + V_l)_{target} = (1 + sT_p) \times \sum V_{d,i,intended} + V_{c,seepage} \tag{8.14}$$

The standard deviation, s, and the intended flow to be delivered to the i-th unit, $V_{d,i,intended}$, were defined above. Values of T_p versus F are listed in Table 8.1.

As in the example of the Los Sauces tertiary unit, the target flow is strongly influenced by the standard deviation, s, of the water delivery ratio and by the acceptability of a water shortage (F in %). The standard deviation depends on the

Figure 8.4 The actual volume of water flowing through an irrigation canal can be measured accurately with a long-throated flume (Bos 1976; Clemmens et al. 1994)

level of technology available to deliver water and on the quality of management and operation. The F-value depends on the climate and on the acceptable number of complaints from water users' groups.

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CRIWAR 2.0 calculates the crop irrigation water requirements of a cropping pattern in an irrigated area. The crop irrigation water requirements consist of two components: potential evapotranspiration, ET_p, minus the effective precipitation, P_e.

The input data of CRIWAR 2.0 are organized through three files; a general data file on the irrigated area, a meteo data file and a cropping pattern file. The cropping pattern file can be composed of 50 CRIWAR programmed crops and of any user-defined crop. For a user-selected combination of general data, meteo data and cropping pattern, CRIWAR creates tables and graphs giving; reference evapotranspiration, crop irrigation water requirements per 10-day period or month, cropping intensity, cropping pattern, effective precipitation, etc. All tables and graphs can be imported into commonly used word-processing software.

Following the 'user manual' part of this book (Chapters 2 through 4), this manual gives theory and information on evapo-transpiration (Chapter 5), effective precipitation (Chapter 6), capillary rise (Chapter 7) and how to transfer the crop irrigation water requirements into the irrigation water requirements of an irrigation command area (Chapter 8).

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